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DESIGN CRITERIA
(CHEMICAL PROPULSION)

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LIQUID ROCKET METAL TANKS AND TANK COMPONENTS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. This document, part of the series on Chemical Propulsion, is one such monograph. A list of all monographs issued to date can be found on the final pages of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that these documents, revised as experience may indicate to be desirable, eventually will provide uniform design practices for NASA space vehicles.

This monograph, "Liquid Rocket Metal Tanks and Tank Components", was prepared under the direction of Howard W. Douglass, Chief, Design Criteria Office, Lewis Research Center; project management was by M. Murray Bailey. The monograph was written by W. A. Wagner of Space Division, Rockwell International Corporation, and was edited by Russell B. Keller, Jr. of Lewis. Significant contributions to the text were made by C. D. Brownfield, Space Division, Rockwell International Corporation. To assure technical accuracy of this document, scientists and engineers throughout the technical community participated in interviews, consultations, and critical review of the text. In particular, Richard A. Morehouse of The Boeing Company; Fred R. Schwartzberg of Martin Marietta Company; Leo M. Thompson of Bell Aerospace Company, Division of Textron; and Gordon T. Smith and Richard T. Barrett of the Lewis Research Center individually and collectively reviewed the monograph in detail.

Comments concerning the technical content of this monograph will be welcomed by the National Aeronautics and Space Administration, Lewis Research Center (Design Criteria Office), Cleveland, Ohio 44135.

May 1974

GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to organize and present, for effective use in design, the significant experience and knowledge accumulated in development and operational programs to date. It reviews and assesses current design practices, and from them establishes firm guidance for achieving greater consistency in design, increased reliability in the end product, and greater efficiency in the design effort. The monograph is organized into two major sections that are preceded by a brief introduction and complemented by a set of references.

The State of the Art, section 2, reviews and discusses the total design problem, and identifies which design elements are involved in successful design. It describes succinctly the current technology pertaining to these elements. When detailed information is required, the best available references are cited. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the *Design Criteria* and Recommended Practices.

The *Design Criteria*, shown in italics in section 3, state clearly and briefly what rule, guide, limitation, or standard must be imposed on each essential design element to assure successful design. The *Design Criteria* can serve effectively as a checklist of rules for the project manager to use in guiding a design or in assessing its adequacy.

The Recommended Practices, also in section 3, state how to satisfy each of the criteria. Whenever possible, the best procedure is described; when this cannot be done concisely, appropriate references are provided. The Recommended Practices, in conjunction with the *Design Criteria*, provide positive guidance to the practicing designer on how to achieve successful design.

Both sections have been organized into decimally numbered subsections so that the subjects within similarly numbered subsections correspond from section to section. The format for the Contents displays this continuity of subject in such a way that a particular aspect of design can be followed through both sections as a discrete subject.

The design criteria monograph is not intended to be a design handbook, a set of specifications, or a design manual. It is a summary and a systematic ordering of the large and loosely organized body of existing successful design techniques and practices. Its value and its merit should be judged on how effectively it makes that material available to and useful to the designer.

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LIQUID ROCKET METAL TANKS AND TANK COMPONENTS

1. INTRODUCTION

The flightweight tanks containing various system fluids are an important part of any liquid propellant rocket propulsion system. They vary in size and shape from a cylindrical tank holding many thousands of gallons of booster propellant to a sphere holding only a few cubic feet of spacecraft pressurant gas at high pressure. The continuous improvement and upgrading of the various codes governing pressure-vessel design and construction are indicative of the emphasis and concern placed on tank design because of the explosive hazard of tankage even under moderate pressures. However, additional guidelines and practices are required to ensure that tanks for aerospace applications are of optimum design. This monograph has been prepared to delineate the significant guidelines and practices for successful design of aerospace tanks and tank components such as expulsion devices, standpipes, and baffles.

The structural-weight efficiency of aerospace tanks strongly influences the payload capabilities. The incentive to minimize tank weight by use of high-strength, brittle materials operated at a high fraction of yield strength must be balanced against the reliability requirements and economic constraints that are inherent in each particular design situation. Many metal alloys under high stress are sensitive both to small inherent flaws and to the effects of various external environments. Flaw growth induced by stress or by environmental conditions has led to tank rupture even at normal operational pressure. Fracture-control methods based on the recently developed technology of linear-elastic fracture mechanics provide a means for minimizing such failures.

Failures of tank assembly components, although usually not as ominous as a tank rupture, have just as surely led to mission failures; for example, expulsion devices and standpipes have failed, thereby preventing proper propellant consumption. The designer therefore must employ the same care for components as for tanks in establishing strength margins, selecting material, and allowing for environmental effects.

The material in this monograph is organized around the major considerations in the design of *metal tanks*. Although these considerations are listed as separate entities, they are interrelated to varying degrees; and these various interactions are discussed. Because of extreme differences in structural complexity, vehicle tanks are treated separately from subsystem tanks. Vehicle tanks are tanks that serve both as primary integral structure of a vehicle and as a container of pressurized propellants. Subsystem tanks are containers of pressurized fluids or gases that are mounted internally in a vehicle, are essentially isolated from adverse vehicle loads, and are of monocoque design.

In the development of a tank, the initial design activity is simply the determination of tank shape or configuration within the constraints of mating vehicle structure or available mounting space. When the basic configuration has been defined, the next activity is material selection. Mechanical properties, fracture toughness, environmental compatibility, cost, availability, and fabrication factors must be considered in material selection. Detail tank and component design follow the material selection. The objective in detail design is to satisfy the tank volume and shape requirements with the selected material in an optimum manner. The significant elements in detail tank design are vehicle-tank sidewall structure, weld joints at bulkhead and attachment junctures, and ports and access openings. Additional design considerations are the influence and effect of fabrication processes on tank and component design and, finally, the testing and inspection that are required to establish confidence in a tank design.

2. STATE OF THE ART

Over the past ten years, hundreds of lightweight, high-strength tanks have been developed for use on liquid rocket propulsion systems. Reference 1 identifies over 75 different programs in which tanks were used. Tables I, II, and III present some of the significant design characteristics of a representative cross section of tank designs dating back to the late 1950's. Such a multitude of programs obviously presents wide variations in factors such as mission duration, mission environment, fluids employed, and fluid energy levels, each of which influence the design of the tanks utilized in a given vehicle.

The largest tanks are the main tanks of the launch vehicles, which must withstand significant compressive loads and flight-induced flexure as well as internal pressure and fluid slosh loads. Typically, there is a single oxidizer tank and a single fuel tank in each main stage of the overall vehicle. Figures 1 and 2 show an exploded view of the primary constituents of the Saturn S-IC booster and S-II stage, respectively.

Each stage or spacecraft of a vehicle complex employs smaller tanks in various subsystems such as reaction control, pressurization, and hydraulic. These tanks are internally mounted, are usually of monocoque design, have integral fluid ports and support provisions, and contain an expulsion device if liquid must be supplied under random low-g conditions.

The Atlas, which was the first booster of major size developed, is unique in that the lightweight monocoque design of the vehicle tanks requires internal pressure to preclude membrane* buckling. The internal common bulkhead, which separates the forward LOX tank and aft RP-1 tank, also requires a positive pressure on the fuel side to prevent structural failure. Stringent weight limitations led to the use of 301 CRES in the extra full hard (XFH) condition for these tanks. The successive cylindrical sections are overlapped, joining being accomplished by spot welds; a seam weld is added at each lap joint to prevent leakage. The longitudinal welds in a particular cylindrical segment are butt welds. The majority of later booster designs are of waffle or frame/stringer sidewall design with tank sections joined by butt welding. The membranes are machined from thick sheet or plate stock, a process that enables incorporation of thickened weld lands, thickened accessory or structural attach points, and stringers that are integral with the membrane.

For the pressure and load range on large-diameter boosters such as Saturn IC and Titan III, hoop tensile forces dictate the membrane (skin) thickness, and additional material (structure) is added as required for longitudinal compressive loads. Aluminum alloys (predominantly 2014-T6 and 2219-T87) have been the primary choice of material because they possess good strength-to-density ratios and excellent ductility and toughness at both room and cryogenic temperatures. Although welding has presented problems, an increased

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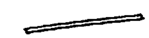
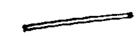
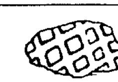
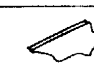
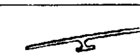
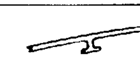
*Terms, symbols, materials, and abbreviations are defined or identified in Appendix B.

Table 1. – Chief Design Features of Vehicle Tanks

Vehicle/System	Working fluid	Tank size inside, in.*	Tank shape	Load per inch, lbm*	Material description: Principal alloy	Thickness, in.: Ends	Thickness, in.: Cyl.	Ultimate factor of safety	Maximum design operating pressure, psig*	Proof pressure, psig	Design burst pressure, psig	Sidewall configuration
Agena/Fuel	UDMH	60 D X 67 L	Cylinder	–	6061-T6 aluminum	0.035 to 0.089	0.060	1.25	55.0	61.0	69.0	
Agena/Oxidizer	IRFNA	60 D X 91 L	Cylinder	–	6061-T6 aluminum	0.051 to 0.096	0.060	1.25	55.0	61.0	69.0	
Atlas/Fuel	RP-1	120 D X 960 L	Cylinder	–	301 SS XFH	0.024 to 0.041	0.028 to 0.038	1.88	60.0	75.0	113.0	
Atlas/Oxidizer	LOX	120 D X 480 L, then taper to 48 D over 120 L	Cylinder	–	301 SS FH	0.016 to 0.024	0.017 to 0.028	1.88	26.0	33.0	49.0	
Centaur/Fuel	LH_2	120 D X 193 L	Cylinder	720 Aft ring	301 SS XFH	0.010 to 0.016	0.014	1.25	26.8	–	–	
Centaur/Oxidizer	LOX	120 D X 120 D X 87 D	Ellipsoid	–	301 SS XFH	0.018 0.014	–	1.25	48.0 at −320° F; 39 at room temp.	–	–	
Saturn IC/Fuel	RP-1	396 D X 517 L	Cylinder	7 300	2219 aluminum	0.167 to 0.202	0.170 to 0.193	1.4	49.3	51.8	69.1	
Saturn IC/Oxidizer	LOX	396 D X 775 L	Cylinder	6 500	2219 aluminum	0.130 to 0.150	0.190 to 0.254	1.4	56.8	66.2	79.4	
Saturn II/Fuel	LH_2	396 D X 656 L	Cylinder	1 400	2014 aluminum	0.067 to 0.116	0.135 to 0.138	1.4	36.7	–	51.4	
Saturn II/Oxidizer	LOX	396 D X 264 L	Oblate spheroid	–	2014 aluminum	0.163 to 0.302	–	1.4	84.4	–	118.0	
Saturn IV/Fuel	LH_2	260 D X 398 L	Cylinder	620	2014 aluminum	0.060	0.123	1.4	42.1	–	59.0	
Saturn IV/Oxidizer	LOX	130 R segments	Incomplete spheroid	–	2014 aluminum	0.086 to 0.092	–	1.4	70.4	–	98.5	
Titan/Fuel	UDMH	120 D X 296 L	Cylinder	3 730	2014-T6 aluminum	0.052 to 0.65	0.079 to 0.119	1.25	66.2	–	82.8	
Titan/Oxidizer	N_2O_4	120 D X 334 L	Cylinder	2 740	2014-T6 aluminum	0.066 to 0.226	0.104 to 0.125	1.25	102.0	–	127.5	

D = diameter, L = length, SS = stainless steel; FH = full hard; XFH = extra full hard.

*Factors for converting U.S. customary units to the International System of Units (SI units) are given in Appendix A.

Table II. – Chief Design Features of Subsystem Tanks

Vehicle/System	Working fluid	Tank size inside, in.	Tank shape	Tank weight, lbm	Material description			Weld description		Operating factor of safety (ultimate)	Maximum design operating pressure, psig	Proof pressure, psig	Design burst pressure, psig
					Principal alloy	Thickness, in.		Type of weld*	Weld thickness, in.				
						Ends	Cyl.						
Agena/Propulsion	Helium	14.8	Sphere	16.0	6Al-4V titanium	–	–	"J" groove	0.175 approx.	1.6	3 600	4 320	5 760
Agena/Propulsion	Helium	14.75	Sphere	11.85	6Al-4V titanium	0.094	–	"V" pressure weld	0.103 approx.	1.6	2 500	3 000	4 000
Agena/Secondary propulsion	UDMH	10 D X 45 L	Cylinder	32.3	A-286 steel	0.018	0.018	"V" groove	0.300	2.0	210	315	420
Agena/Secondary propulsion	Nitrogen	12.45	Sphere	16.0	6Al-4V titanium	–	–	Pressure weld	0.222	2.23	4 500	7 500	10 000
Agena/Secondary propulsion	N_2H_4/MMH	10.8 D X 47 L	Cylinder	17.5	6061-T6 aluminum	–	–	"V" groove	0.110	1.76	285	375	500
Apollo CM/Reaction control	MMH	12.5 D X 17.3 L	Cylinder	7.2	6Al-4V titanium	0.027	–	Butt	0.043	1.5	360	480	540
Apollo SM/Reaction control	N_2O_4	12.5 D X 28.6 L	Cylinder	8.7	6Al-4V titanium	0.022	–	Butt	0.043	1.5	248	331	372
Atlas/Propulsion	Helium	12.4	Sphere	9.5	17-7 PH CRES	0.065	–	"J" groove	0.085 approx.	2.0	1 000	1 600	2 000
Atlas/Propulsion	Helium	24.230	Sphere	65.0	6Al-4V titanium	0.190	–	"U" groove	0.265	1.67	3 000	4 000	5 000
Atlas/Pneumatic	Helium	20.775	Sphere	50.0	6Al-4V titanium	0.192	–	"J" groove	0.262	1.67	3 000	4 000	5 000
Centaur/Propulsion	Helium	24.26	Sphere	79.0	6Al-4V titanium	0.224	–	"J" groove	0.351	1.67	3 000	4 000	5 000
Delta/APS	Nitrogen	7.87	Sphere	2.5	6Al-4V titanium	0.067	–	"J" groove	0.285	1.27	4 000	4 450	5 062

(continued)

Table II. – Chief Design Features of Subsystem Tanks (continued)

Vehicle/System	Working fluid	Tank size inside, in.	Tank shape	Tank weight, lbm	Material description			Weld description		Operating factor of safety (ultimate)	Maximum design operating pressure, psig	Proof pressure, psig	Design burst pressure, psig
					Principal alloy	Thickness, in.		Type of weld*	Weld thickness, in.				
						Ends	Cyl.						
Gemini/OAMS	Helium	14.87	Sphere	19.2	6Al-4V titanium	–	–	"J" groove	0.030	2.23	3 000	5 000	6 700
Gemini/RCS	N_2O_4	22.0	Sphere	8.0	6Al-4V titanium	0.025	–	"J" groove	0.032 approx.	2.33	300	500	700
Gemini/Reentry	MMH	5.1 D X 30.9 L	Cylinder	4.3	6Al-4V titanium	–	–	"V" groove	0.020	2.27	295	500	670
Intelsat III/ACS	N_2H_4	9.56	Sphere	1.6	6Al-4V titanium	0.018	–	Burndown	–	2.0	600	900	1 200
LEM Ascent/ Propulsion	A-50 or N_2O_4	49.4	Sphere	75.2	6Al-4V titanium	0.032	–	"V" groove	0.060	1.35	250	333	338
Lunar Orbiter/ Propulsion	A-50	12.5 D X 17.3 L	Cylinder	7.2	6Al-4V titanium	0.027	0.027	Butt	0.043	2.28	236	480	540
Mariner Mars/ACS	Nitrogen	5.61	Sphere	2.57	6Al-4V titanium	0.143	–	"U" groove	0.171	2.2	6 000	10 700	13 200
Mercury/RCS	H_2O_2	3.5 D X 75.0 L	Toroid	8.9	6061-T6 aluminum	–	–	Butt	0.045 approx.	2.0	500	750	1 000
Mercury/RCS	H_2O_2	10.0	Sphere	7.1	6061-T6 aluminum	–	–	Butt	0.045 approx.	2.0	500	750	1 000
Minuteman II/Thrust vector control	Freon	48 O.D. 6.37 cross section	Toroid	62.0	17-7 PH CRES	0.109	–	"U" groove	0.197	1.67	750	1 015	1 250
Nimbus/Control	Freon	12.08	Sphere	–	6Al-4V titanium	–	–	"V" groove	0.139	2.0	2 500	3 750	5 000
Nimbus/Control	Freon	9.74	Sphere	6.7	6Al-4V titanium	0.130	–	"J" groove	0.169 approx.	3.98	2 015	4 015	8 015

Table II. – Chief Design Features of Subsystem Tanks (concluded)

Vehicle/System	Working fluid	Tank size inside, in.	Tank shape	Tank weight, lbm	Material description: Principal alloy	Material description: Thickness, in. Ends	Material description: Thickness, in. Cyl.	Weld description: Type of weld*	Weld description: Weld thickness, in.	Operating factor of safety (ultimate)	Maximum design operating pressure, psig	Proof pressure, psig	Design burst pressure, psig
Polaris/ACS	Nitrogen	13.51	Sphere	13.5	6Al-4V titanium	0.125	–	Butt	0.137 approx.	2.0	2 515	3 765	5 015
Saturn IB/Coolant	Nitrogen	4.638	Sphere	1.02	6Al-4V titanium	0.071	–	"V" groove	0.075	2.2	3 000	5 000	6 600
Saturn IC/Control	Nitrogen	16.75	Sphere	27.0	6Al-4V titanium	–	–	"J" groove	0.220	2.2	3 000	5 000	6 600
Saturn II/Pneumatic	Helium	17.150	Sphere	50.0	6Al-4V titanium	0.225	–	"J" groove	0.326	2.46	3 250	5 000	8 000
Saturn II/Pneumatic	Helium	10.2	Sphere	5.0	6Al-4V titanium	0.072	–	"J" groove	0.094 approx.	2.5	800	1 200	2 000
Saturn IV/Propulsion	MMH	12.5 D X 38.8 L	Cylinder	15.75	6Al-4V titanium	0.029	0.029	Butt	0.043	2.0	275	413	550
Surveyor/Propulsion	N_2O_4	9.830 D X 13.13 L	Cylinder	2.67	7178-T6 aluminum	0.365	0.365	Butt	0.105	1.25	830	960	1 038
Surveyor/Propulsion	MON 10	10.0 D X 15.4 L	Cylinder	3.34	6Al-4V titanium	0.034	0.034	"V" groove	0.044 approx.	1.25	840	970	1 050
Surveyor/Propulsion	Helium/ Nitrogen	9.138	Sphere	27.8	6Al-4V titanium	0.273	–	"J" groove	0.355 approx.	2.2	5 175	7 762	11 385
Titan I/Propulsion	Helium	26.0	Sphere	158.0	6061-T6 aluminum	0.625	–	Butt	–	1.21	3 300	3 400	3 960
Titan II/Pneumatic	Helium	9.86	Sphere	7.0	6Al-4V titanium	0.072	–	"J" groove	0.093 approx.	5.0	800	2 000	4 000
Titan IIIC/Propulsion	Nitrogen	9.49	Sphere	5.5	6Al-4V titanium	–	–	"V" groove	0.124	2.31	3 000	5 300	6 950
Titan IIIC/Propulsion	Helium	34.0	Sphere	200.0	6Al-4V titanium	0.381	–	"J" groove	0.490 approx.	2.05	3 600	6 179	7 400
Titan IIIC/ACS	N_2O_4	14.18	Sphere	7.3	6066-T6 aluminum	0.058	–	"V" groove	0.070 approx.	2.42	290	525	700

*Except for two instances of pressure welds noted, all welds were tungsten-inert-gas (TIG) welds.

Table III. – Chief Design Features of Positive-Expulsion Tanks

Vehicle/System	Working fluid	Tank size inside, in.	Tank shape	Tank weight, lbm	Material description			Operating factor of safety (ultimate)	Maximum design operating pressure, psig	Proof pressure, psig	Design burst pressure, psig	Expulsion device
					Principal alloy	Thickness, in.						
						Ends	Cyl.					
Advent/RCS	UDMH/N_2H_4	16	Sphere	6.6	17-7 PH steel	0.016	–	2.0	185	280	370	Bladder
Agena/Propulsion	IRFNA	4.2 D X 5.9 L	Cylinder	6.9	AM355 steel	0.060	0.060	–	1 970	–	–	Metal bellows
Agena/Propulsion	UDMH	10 D X 45 L	Cylinder	32.3	A-286 steel	0.018	0.018	2.0	210	315	420	Metal bellows
Agena/SPS	N_2O_4/NO	10 D X 29 L	Cylinder	11.3	6061-T6 aluminum	0.050	0.050	2.0	210	315	420	Bladder
Apollo CM/RCS	N_2O_4	12.5 D X 19.9 L	Cylinder	7.9	6Al-4V titanium	0.027	0.027	1.5	360	480	540	Bladder
Apollo LEM Ascent/ECS	Water	14.5	Sphere	6.1	6061-T6 aluminum	0.032	–	–	54	–	–	Bladder
Apollo LEM/RCS	UDMH/N_2H_4	12.5 D X 32,2 L	Cylinder	10.1	6Al-4V titanium	0.023	0.025	1.5	250	333	375	Bladder
Centaur/RCS	H_2O_2	21.5	Sphere	28.3	6061-T6 aluminum	0.080	–	2.0	300	450	600	Bladder
Gemini/OAMS	MMH	20	Sphere	8.0	6Al-4V titanium	0.025	–	2.3	300	500	700	Bladder
Gemini/RCS	N_2O_4	5 D X 25 L	Cylinder	3.9	6Al-4V titanium	–	–	2.3	295	500	670	Bladder
Lunar Orbiter/ACS	UDMH/N_2H_4	12.5 D X 17.3 L	Cylinder	7.1	6Al-4V titanium	0.027	0.027	2.3	236	480	540	Bladder
Mariner '69/RCS	N_2H_4	11	Sphere	2.2	6Al-4V titanium	0.018	–	3.0	308	620	922	Bladder

(continued)

Table III. – Chief Design Features of Positive-Expulsion Tanks (concluded)

Vehicle/System	Working fluid	Tank size inside, in.	Tank shape	Tank weight, lbm	Material description: Principal alloy	Material description: Thickness, in.: Ends	Material description: Thickness, in.: Cyl.	Operating factor of safety (ultimate)	Maximum design operating pressure, psig	Proof pressure, psig	Design burst pressure, psig	Expulsion device
Mariner '71/Propulsion	N_2O_4	29.5	Sphere	22.5	6Al-4V titanium	0.031	–	2.0	295	450	600	Bladder
Mercury/RCS	H_2O_2	10.0	Sphere	7.1	6061-T6 aluminum	0.080	–	2.0	500	750	1 000	Bladder
Mercury/RCS	H_2O_2	3.5 D X 75 L	Toroidal	8.9	6061-T6 aluminum	0.058	0.058	2.0	500	750	1 000	Bladder
Minuteman/ Post boost	MMH	13.8 D X 37.7 L	Cylinder	46.3	A-286 steel	–	–	1.9	260	275	345	Metal bellows
Minuteman II/Second stage TVC	Freon	48.0 O.D., 6.37 cross section	Toroidal	62.0	17-7 PH steel	0.070 to 0.095	–	1.7	750	1 015	1 250	Bladder
Rascal/Propulsion	RP-1	47.8 D X 48 L	Cylinder	170.0	6061-T6 aluminum	0.125	0.125	2.0	50	75	100	Bladder
Saturn S-IV-B/APS	MMH	12.5 D X 38.8 L	Cylinder	15.8	6Al-4V titanium	0.028	0.029	2.0	275	413	550	Bladder
Scout/Propulsion	H_2O_2	6.2 D X 12 L	Cylinder	4.0	6061-T6 aluminum	0.125	0.125	2.5	500	750	1 250	Bladder
SE-5/ACS	N_2O_4	10.8 D X 47 L	Cylinder	17.5	6061-T6 aluminum	–	–	1.75	285	375	500	Bladder
Surveyor/RCS	N_2O_4/NO	10 D X 15 L	Cylinder	2.2	6Al-4V titanium	0.017	0.017	1.25	830	955	1 038	Bladder
Titan III Trans-stage/ACS	N_2O_4	28.2 D X 33.2 L	Cylinder	52.0	6Al-4V titanium	0.050	0.105	1.9	400	600	760	Diaphragm
Titan III Trans-stage/ACS	UDMH/N_2H_4	14.3	Sphere	7.2	6066-T6 aluminum	0.058	–	2.4	290	525	700	Bladder
Upstage/Propulsion	B_5H_9	4.6 D X 30.5 L	Cylinder	24.5	Maraging steel(1)	0.057	0.062	2.0	5 000	7 500	10 000	Piston

(1)With 6061-T6 Aluminum liner.

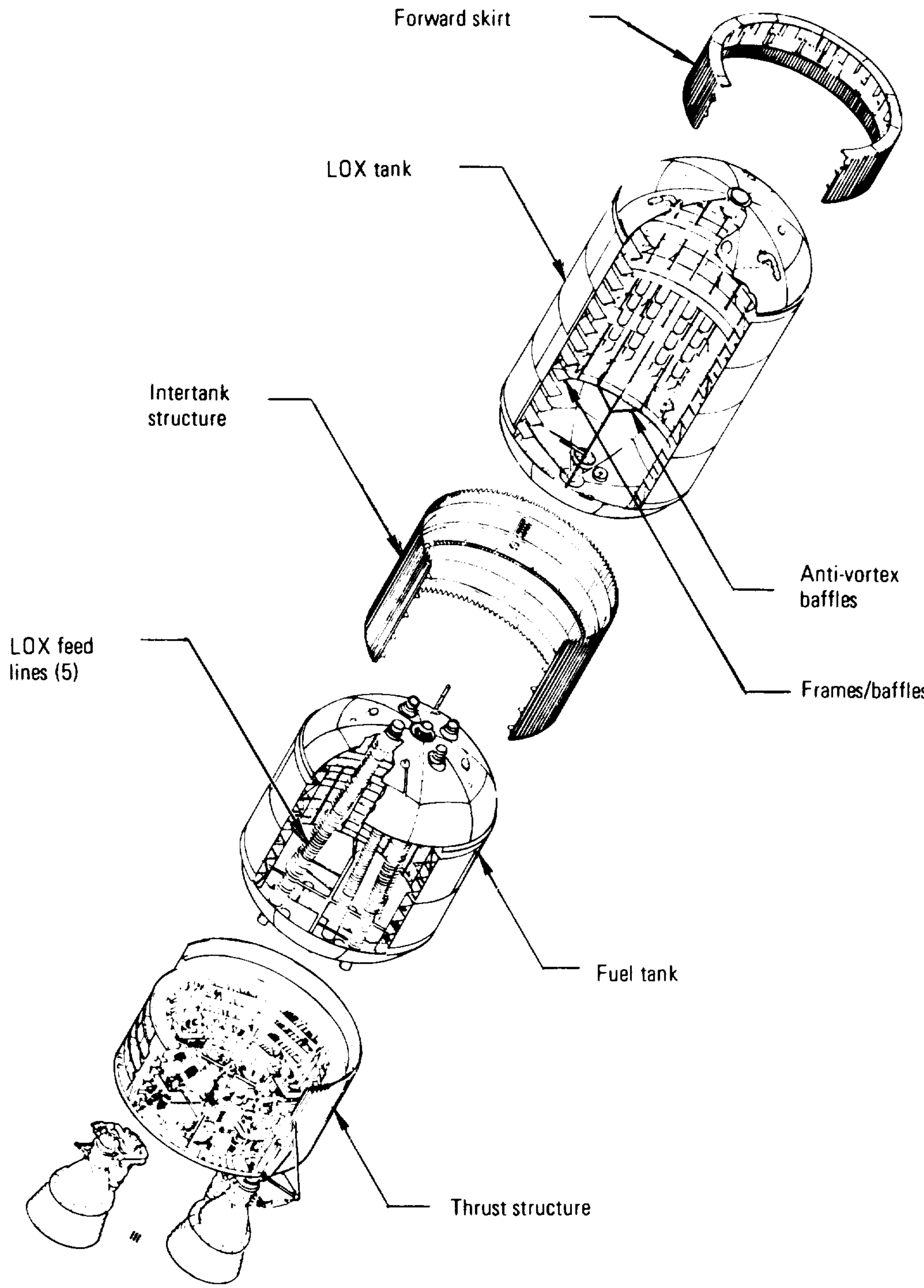


Figure 1. – Exploded view of major components for Saturn IC booster.

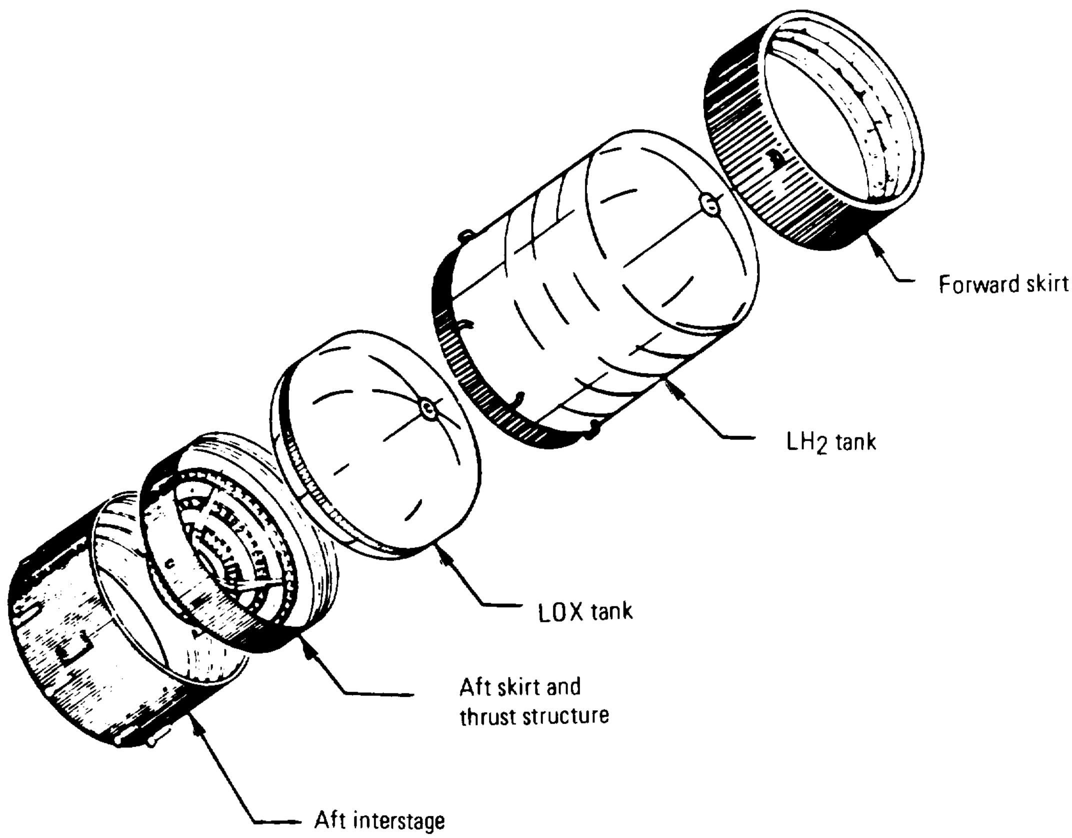


Figure 2. – Exploded view of major components for Saturn S-II stage.

knowledge of proper tooling, environmental control, joint preparation, and welding procedures as well as improved techniques for inspection, proof testing, and repair have made it possible to produce consistently reliable welded joints in these materials.

Although vehicle tanks vary significantly in size, load per inch, and structural complexity, all these tanks have complied with the following principles:

(1) Gross stress levels at proof and operating conditions have been maintained below yield strength of the material.

(2) Local yielding is permitted around discontinuities if structural integrity is not compromised.

(3) The factor of safety provides adequate margin for uncertainties in stress analysis, applied loading, and fabrication and permits suitable margin for unavoidable strength degradation during service life.

(4) The factor of safety is based primarily on experience, qualitative assessment of uncertainties of the specific design, and reliability requirements.

(5) Fracture strength is greater than yield and equal to or greater than minimum guaranteed ultimate strength.

(6) Flaws or defects are found by inspection and repaired if permissible.

For the subsystem tanks summarized in table II, it is notable that in none of the design features shown are there data that indicate a changing trend in tank design. These tanks also comply with the principles set forth above for vehicle tanks. The weld joints are exclusively butt welds. The preweld configurations of the weld joints are predominantly "V" or "J" groove for the thicker membrane tanks and "burndown" lips for the thinner membrane tanks. With few exceptions, welding is accomplished by the tungsten-inert-gas (TIG) method.

Various types of positive expulsion devices have been used successfully (table III); each type of device has advantages and disadvantages. Since the expulsion device must be compatible with the ultimate tank usage requirements, no particular expulsion device can be considered universally superior; thus, the degree of usage of a particular type of expulsion device does not necessarily mean that it is the superior method. In the past decade, the advances in the technology of positive-expulsion devices have been consistent with the increasing severity of space mission environments. Problems of material compatibility with propellants, propellant/gas permeation through thin bladder membranes, operation at cryogenic temperatures, and multicycle requirements, to name a few, have been solved. It can be expected that this technology will continue to advance as more prolonged space explorations are undertaken in the future.

In summary, the basic design approach for vehicle tanks, subsystem tanks, and expulsion devices to a large degree has not changed significantly over the past decade. Considerable development has occurred in the technologies associated with the production of lightweight, high-quality pressure vessels, especially in large sizes, and in the techniques for ensuring that these tanks meet the unusually high levels of structural reliability demanded in complex aerospace vehicle systems. Advances have been most notable in the following areas:

(1) Development of fracture-mechanics concepts and of methods for applying these concepts to pressure-vessel fracture control (refs. 2, 3, and 4)

(2) Development of alloys with improved strength, toughness, and fabricability

(3) Development of information on interaction effects between structural materials and environments

(4) Development of equipment and fabrication techniques capable of producing, forming, and welding large, thin-wall components

(5) Development of improved NDI (nondestructive inspection) techniques and equipment.

Although advances in fracture mechanics and NDI techniques have been realized, the exact nature of application to such basic tank design decisions as material selection, stress level selection, and definition of proof-test requirements remains a subject of current controversy and considerable misunderstanding among structural designers.

2.1 TANK CONFIGURATION

In the first phase of design, where the shape and size of the tank are established, vehicle tanks and subsystem tanks present significantly different problems to the designer. Vehicle tanks are an integral part of the vehicle structure and must sustain the compressive loads of the overall vehicle stack. They are operated at comparatively low internal pressures (usually less than 100 psig) and must be dimensionally compatible with the adjacent stage or payload. Extensive consideration must be given to bulkhead shape because it affects tank length and the requirements for structural stiffening, the extent depending on material used. Subsystem tanks usually are of monocoque design, are internally mounted within the vehicle, usually operate at high stress levels, and are insulated from vehicle structure deflection by appropriately designed mountings. Except where problems in installation space arise, the tank shape usually is determined on the basis of structural efficiency.

2.1.1 Vehicle-Tank Optimization

The design of a vehicle tank begins with consideration of the entire launch vehicle in terms of mission requirements. The initial study often is accomplished with the aid of computerized vehicle-synthesis programs (ref. 5), which perform extensive preliminary studies designed to establish overall vehicle configuration and to provide constraints for the detail design. A large number of options are evaluated to arrive at the final vehicle configuration. These options include the number of stages; the number, size, and type of engine for each stage; the selection and location of propellants for each stage; and the length, diameter, and material of each tank. Preliminary design studies are iterative processes, and the design or structural analysis is limited to what is necessary to establish feasibility and to arrive at a reasonably accurate determination of mass properties such as center of gravity, center of pressure, mass distribution, moment of inertia, and total weight. These properties are integrated with aerodynamic forces and tank internal pressures to determine vehicle net shear, bending, and axial loads. The vehicle structural configuration is modified to meet these requirements and the process iterated until it converges to an optimum vehicle design.

The final output of the preliminary design provides the constraints for the next step: the detail design and analysis. These constraints are definition of the tank diameter and length, tank internal pressure requirements, and propellant type, location, and volume. Additional constraints are added by program management. These constraints, based on the type of mission coupled with judgment and past experience, are the factor of safety; criteria for failure mode of tank pressure regulator or vent valve; method of combining loads; and "free standing" capability on the launch pad (unpressurized) with any or all other stages full or empty.

2.1.2 Subsystem-Tank Optimization

As in the case of the vehicle tanks, the primary design objective for the smaller subsystem tanks usually is optimum design in terms of minimum weight or minimum design margin without impairment of reliability. For the smaller subsystem tanks, however, it should be emphasized that an overview of costs for a liquid rocket vehicle program (with multiple subsystems) may impose considerations of using existing forging dies or may require tank design commonality between subsystems; either requirement preempts the minimum weight/margin goal. For purposes of this monograph, however, only the optimization of design for a new, minimum-weight tank will be discussed.

Unlike vehicle tanks, which invariably are large liquid-carrying tanks, subsystem tanks may be designed in any one of three configurations: liquid-carrying only, liquid-carrying with a positive expulsion device, and gas-carrying. Each type presents distinct design problems.

Liquid-carrying tanks. – Optimization of a liquid-carrying tank is relatively easy because the fluids are considered incompressible, and therefore usable fluid volume and hence tank volume becomes a constant. It is advantageous to keep the liquid working pressure at the lowest possible value that permits minimum wall thicknesses. Once the basic fluid volume to accomplish a vehicle mission is established, the various delta volumes typical of most operating rocket systems are identified and added. Since fluids expand as temperature increases, ullage volumes consistent with the predicted usage environment are added. Loading errors, fluid displacement of any internal structure and accessories, and fluid traps are compensated for by increased tank size. If the rocket system is bipropellant, feedout imbalance is considered; and, if a cryogenic fluid is involved, the attendant boiloff loss must be offset by an appropriate increment during filling.

Following the identification of all volume increments and the determination of total fluid volume, selection of tank shape is the next decision point. Cylinders with hemispherical ends and spheres are the most common shapes for the smaller subsystem tanks. Limitations of installation space and mounting difficulties frequently eliminate the spherical tank as a contender. In some cases, considerations of space in a complex, compact liquid rocket vehicle dictate the use of other geometrical shapes (e.g., a torus, or a cone with hemispherical ends). The design considerations for these special configurations, however, are the same as those for the more conventional shapes. A disadvantage of the torus and the cylinder with $L/D < 5$ (no longitudinal weld) is the weld-length requirement.

Liquid-carrying tanks with positive expulsion devices. – Although the foregoing statements for liquid-only tanks are applicable to positive expulsion tanks, additional problems in establishing tank size and shape optimization are introduced by the positive expulsion device. The design of expulsion device and tank shell are so extensively interdependent that parallel, simultaneous designs are essentially mandatory. A decision that is made early in the design effort is the type of expulsion device that will be used. An early decision is necessary because of the wide variations in expulsion-device installation requirements. For example, a flexible Teflon bladder can be folded and installed in a tank through a comparatively small opening (e.g., 4-in. diam.), whereas a corrugated metal diaphragm requires either a bolted flange or appropriate weld joint at the tank girth. Additional tank-volume deltas introduced by the expulsion device that must be considered are (1) liquid residuals due to inability of the device to expel all the liquid from the tank's liquid compartment, and (2) volume displacement of the device and associated working clearance required by the device.

Gas-carrying tanks. – With gas pressurants, there is the added problem of significant change in volume and pressure with temperature. The temperature gradients resulting from heat of compression during tank charging and decompression cooling during pressurant discharge as well as from the influence of external environments must be considered so that adequate strength margins and sufficient volume at time of pressurant demand can be ensured. Tank pressure charging usually can be programmed to ensure temperature/pressure combinations that are consistent with a tank's capabilities. The pressurant consumption schedule, on the other hand, usually is not known precisely but rather must be predicted for a particular mission. These hypothetical consumption schedules, necessarily conservative, become the basis for the depletion analysis. The long lead time required for tank development frequently forces the tank designer to finalize his design and commit to material and forging procurement far in advance of refined mission information. When the design involves comparatively large tanks, the designer must employ keen judgment in finalizing dimensions and tolerances. For example, a wall thickness tolerance of 0.005 in. on a 40-in.-diam. sphere constructed of 6Al-4V-titanium will affect its weight by over 3.5 pounds (4 percent).

Because of greater structural efficiency, spherical tanks provide a weight advantage over other configurations. In contrast to liquid-carrying tanks, it is advantageous to design gas-pressurant tanks to the highest working pressure consistent with the capabilities of the associated downstream system and thereby attain minimum diameter (or minimum surface area).

2.2 TANK MATERIAL

Many different material characteristics may be of interest in the design and development of pressure vessels. However, certain characteristics are of primary importance and can determine the success or failure of such a project. These characteristics are identified and considered early in the material evaluation and selection phases of the program. Material selection usually is based primarily on the following properties:

- Strength/weight efficiency under critical load/temperature conditions (or other critical failure conditions)
- Fabricability (capability of being fabricated into the desired configurations and sizes without loss of properties)
- Compatibility with all anticipated environments
- Fracture toughness and resistance to subcritical flaw growth
- Availability of shapes and sizes within required schedules
- Costs of materials and material processing and fabrication.

The most efficient material for tank construction, from the standpoint of load-carrying ability versus weight, depends upon the type of critical loading, principally whether tension or compression. Internal pressure usually is the critical load in all tanks that do not form an integral part of the vehicle structure. These tanks include most upper-stage and support-system tanks. In such applications, the strength/weight efficiency of candidate materials can be compared on the basis of the ratio of usable tensile strength to weight. Usable tensile strength includes provision for the presence of flaws that are of a size below the limit of reliable NDI detectability or below the size that can be screened by a properly designed proof test. The vehicle tanks for the first and intermediate stages may be critical either in compressive buckling due to boost and aerodynamic forces, or in tension due to internal pressure alone or in combination with structural loads. Materials that are efficient in compressive buckling generally have a high ratio of elastic modulus to density and a high ratio of compressive yield strength to density. However, to compare accurately the efficiency of materials for a compressively loaded structure, it is usually necessary to utilize a structural index that represents the structural configuration and the loading anticipated. This subject is treated in references 6 and 7.

2.2.1 Mechanical Properties

The mechanical properties of concern in the design and analysis of propulsion-system tanks are ultimate tensile strength (F_{tu}), which governs ultimate burst pressure under ductile failure conditions; tensile yield strength (F_{ty}), because of the requirement that there be no yielding either at limit load conditions or during proof testing; compressive yield strength (F_{cy}) for compression critical structures; and the material elastic properties (E, G, and ν). Shear and bearing strength properties (F_{su}, F_{bru}, and F_{bry}) apply to design details such as mechanical attachments and are not normally important factors in the selection of materials.

High-cycle, low-stress fatigue data sometimes are required to evaluate the effects of structural vibration or severe acoustic environment. Low-cycle, high-stress fatigue data often are used to evaluate the effects of multiple pressurization cycles. The material properties utilized in fracture-mechanics analyses are discussed in section 2.2.4.

The effects of a number of important variables on mechanical properties must be considered. These variables include temperature, thermal exposure, duration of loading, biaxiality and triaxiality of loading, rate of loading, and unusual environments such as corrosive fluids and radiation. Design properties are determined for base metal and welds and sometimes for weld heat-affected zones. The effects of loading direction with respect to base-metal grain orientation are considered. Properties along the direction of the weld bead as well as across the weld are evaluated. The effects of all processing, forming, and heat treatments on material design properties are evaluated.

Whenever possible, the precise values of the material mechanical properties used in design and analysis (the "design allowables") are determined by methods that result in consistent levels of reliability for all materials and conditions of application and service. The military handbooks, MIL-HDBK-5B (ref. 8) for metals and MIL-HDBK-17A (ref. 9) for plastics, contain considerable design property data. Nearly all other sources of materials properties data, unless explicity stated otherwise, contain only typical values that are not suitable *per se* as design values.

The methods used to compute design allowable strengths of unflawed materials for MIL-HDBK-5B are covered in MIL-HDBK-5B Guidelines for the Presentation of Data (ref. 8, ch. 9). Two reliability levels are observed, "A" values, which must be met or exceeded by the product 99 percent of the time, and "B" values, which must be met or exceeded 90 percent of the time. In both values, a statistical confidence level of 95 percent is observed. "A" allowables are used for single-load-path structures such as pressure vessels.

The determination of design property values for welds presents some special problems. Design values are not currently available in reference 8 for welded alloys of interest for aerospace pressure vessels. Weld test data that are available in the literature can be used only as a guide to the values that might be reliably obtained in any given welding setup. The many variables that affect weld quality and strength are discussed further in section 2.2.2.2 of this monograph and treated in detail in reference 10; methods for determining weld allowables are also discussed in the same reference.

The basic approach for determining weld allowables that is described in reference 10 is similar to the approach recommended in the MIL-HDBK-5B Guidelines (ref. 8, ch. 9) for metals in general (assuming that process control is exercised over all of the significant welding variables) with but one important exception: the minimum weld strength determined by statistical analysis of test data on weld coupons may be given a further reduction to account for differences between the behavior of coupons and welded structures. This reduction factor has been termed a "coupon/structure ratio" (ref. 10, p. 71) and is evaluated by comparative tests of coupons and representative structures such as subscale tanks. Values of this ratio used to establish allowable weld strengths for tanks and other structures on the Apollo spacecraft and Saturn S-II stage have been in the range of 0.80 to 0.90 (10 to 20 percent reduction in strength).

2.2.1.1 TEMPERATURE EFFECTS ON PROPERTIES

Reduced temperatures tend to increase material mechanical strength properties, but often decrease material ductility and toughness values. Such strength increases sometimes are utilized in the design and analysis of tanks intended for the containment of cryogens when a significant weight saving can be realized. However, it is then necessary to ensure that the fracture toughness of the material is adequate for the anticipated operational and proof-testing conditions; this subject is treated in detail in section 2.2.4. It is also necessary to ensure that room-temperature tank pressurizations can be limited to values that are consistent with the lower room-temperature mechanical properties.

Elevated temperatures tend to reduce material mechanical properties. For some materials (e.g., titanium alloys), even a small increase in temperature above room temperature results in a significant reduction in strength (approximately 10 percent at 200° F). Temperature increases on this order can result from compression heating during pressurization of high-pressure gas containers when a proper heat exchanger is not used. If such effects are not considered, yielding may occur in tanks fabricated from titanium and other alloys that are sensitive to temperature.

Exposure of metals to elevated temperatures for extended periods of time can cause permanent changes in mechanical strength properties, normally reductions. The temperatures at which such changes occur usually are near or above the material's aging or tempering temperature. However, exposure of very long duration (months or years) can result in strength decreases at temperatures well below the normal aging temperatures.

2.2.1.2 FATIGUE STRENGTH

Fluid-containing tanks often are required to withstand a fairly large number of cycles of pressurization. Such cycles occur during tank acceptance testing, integrated system testing, tests and operations performed after delivery of spacecraft, and, of course, service pressurizations. Typically, the total number of such cycles can approach and sometimes exceed one hundred in number. Tank failures have occurred as a result of such repeated pressurizations. Such low-cycle fatigue failures usually originate at stress-concentration points including preexisting cracks or crack-like flaws. The development (nucleation) of cracks tends to occur more readily in materials of limited ductility and in locations in which poor design or fabrication techniques provide localized regions of high stress. Crack nucleation is avoided by a combination of proper design, material selection, fabrication techniques, and quality control, and by demonstration of the ability of hardware to meet cyclic pressurization requirements during qualification testing. The avoidance of failures resulting from the growth of preexisting cracks during pressure cycles is discussed in section 2.2.4.

2.2.1.3 CREEP

Creep is the time-dependent deformation of material under prolonged stress. Pressurization stresses in tanks tend to be long in duration and high in value with respect to material yield strengths. Such stress-time histories are likely to cause significant creep in materials at temperatures for which any creep tendencies have been observed. Although creep is usually associated with high temperatures, especially as related to the temperature at which metallurgical processes such as aging or the relief of cold-working effects occur, at least one notable exception to this rule has been observed: the creep of titanium and titanium alloys at room temperature and at moderately elevated temperatures. The temperature range of this phenomenon is from a little below room temperature to about 600° F, with the minimum creep resistance (in ratio to material static yield strength) occurring in the region of 200° to 350° F. Data on low-temperature creep in titanium alloys are available in references 11 and 12. The conventional creep of titanium becomes significant at temperatures above about 750° F; however, the behavior of metals at high temperatures (above about 300° F) is considered outside the scope of this monograph.

Aluminum alloys also exhibit a slight tendency to creep at room temperature; however, the effect is negligible for loading times less than 1000 hours. For longer loading times or for shorter times at temperatures above 175° F, creep of aluminum can become significant. Data on the creep of aluminum alloys at room and elevated temperatures are provided in reference 13.

2.2.1.4 BIAXIAL-STRESS PROPERTIES

The multiaxial loading of metals can have significant effects on material properties that may or may not have impact on tank design but are an important consideration in the interpretation of pressure-test results.

The biaxial tensile stress fields that normally exist in pressurized tanks may improve material performance, may have no discernible effects, or may even deteriorate performance. Materials that are ductile, homogeneous, and isotropic may show an increase in tensile load-carrying ability, the amount depending on the biaxial stress ratio. The maximum effect usually occurs at a biaxial tensile-stress ratio of 2:1. In carefully conducted material tests, the magnitude of this effect tends to be on the order of that predicted by the Von Mises criterion (also termed the octahedral-shear-stress theory and the distortion-energy theory). According to this theory, the equation for the effective stress for yielding in an element subjected to a complex stress field is

$$\sigma_{eff} = (1/\sqrt{2})\sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2} \quad (1)$$

where

σ_{eff} = effective normal stress

σ_x, σ_y, and σ_z = principal stresses, i.e., normal stresses acting on three mutually perpendicular planes of zero shear stress

Anisotropic materials [e.g., "textured" titanium (titanium processed to obtain preferred orientations of the individual crystals or grains)] do not fit equation (1). The effects of biaxial stresses on such materials and the equation that applies are described in reference 14. In addition, many homogeneous and nondirectional alloys do not appear to behave in full accordance with the distortion-energy concept.

The difficulty and cost of accurately evaluating biaxial strengthening effects, together with the problems associated with correctly applying them, has frequently resulted in these effects being neglected in the design of liquid rocket propulsion-system tanks. On the other hand, the existence of such effects should be considered in the evaluation of burst-test results.

There appears to be a possibility that some materials are reduced in strength when subjected to biaxial tension. This effect could occur with low-elongation materials in a 1:1 biaxial tensile-stress field. This stress state (typical of a spherical tank) limits the ductility effects to the plane that includes the material thickness dimension. A material having limited ductility in the thickness direction will tend to behave in a brittle fashion in such a stress field.

The question as to the possibility of decreases in material resistance to crack propagation due to biaxial tensile stresses appears to remain unresolved. Data reported in reference 15 appear to indicate the existence of such reductions. Until the effects of biaxial loading on the properties of materials regarding growth of critical and subcritical flaws are more fully established, it should be assumed that biaxial loading may decrease and probably will not benefit these properties.

2.2.2 Fabrication Considerations

Fabricability is one of the determining characteristics in the choice of materials for aerospace vehicle pressure vessels. Not all high-strength structural materials can be fabricated economically into reliable vessels. The following essential requirements must be satisfied:

(1) The material must be available in suitable forms, sizes, and levels of quality within the necessary schedules.

(2) The material must be capable of being formed and machined to the required configurations, on the available equipment, and at the material thicknesses and strength levels determined to be appropriate.

(3) The material (alloy) must possess sufficient weldability to suit proposed methods of assembly that involve welding.

(4) The material thermal processing requirements must be capable of being met, within existing economic restrictions, on actual parts or assemblies for which thermal processing will be necessary.

2.2.2.1 SHAPING AND FORMING

Methods of fabrication that have been used to produce metal pressure vessels for aerospace vehicles are compared in table IV (adapted from ref. 16). The factors of size, shape, and material formability have considerable influence on the suitability of desired material and on the methods of fabrication and heat treatment that can be employed. Large size in particular often limits the selection of fabrication methods and heat treatments. Such restrictions may have impact on the optimum material selections. Also, large size often causes the relief of weld residual stresses in completed vessels to be economically if not

Table IV. – Comparison of Fabrication Methods for Pressure-Vessel Components (adapted from ref. 16)

Component	Fabrication method	Advantages	Disadvantages
End domes (complete heads)	Drawing: Hydropress (trapped rubber forming)	Moderate production rate Moderate tooling costs Larger sizes than hydroform	Part size and thickness limited Temperature limited Poor control of thickness
	Hydroform (hydraulic fluid forming)	High production rate Better thickness control than hydropress	Limited to small sizes Temperature limited Relatively high tooling costs
	High-Energy-Rate Forming: Explosive	Very large potential sizes (depending on available facility) Good reproducibility Low to moderate tooling costs	Limited to cold forming Low production rate Limited availability of facilities
	Electrical (including spark discharge and magneto-dynamics)	High production rate Good reproducibility	Limited to small sizes Requires specialized equipment and tooling
	Spinning: Shear	Permits integral bosses and skirts Can handle thick material Good thickness control Spinning can be performed hot	Size limited Limited availability of equipment
	Conventional (manual or power)	Moderately large sizes Low tooling costs	Poor thickness control Permits no integral details as formed Temperature limited Thickness limited Low production rate Requires ductile material
	Forging	Not limited to materials with cold- or warm-forming ability Permits complex configurations Permits integral attachments	Size limited High costs Requires considerable machining Low production rate
	Segmenting (formed and welded segments)	Large size capability (starting with smaller individual parts) Reduces difficulty and cost of forming	High total costs – tooling, welding, and inspection Potential for reduced reliability due to increased welding Poor dimensional control Very low production rate
Cylinders	Rolling and Welding	Accommodates large sizes Low cost, simple process	Potential for reduced reliability due to longitudinal weld Permits no integral reinforcements as fabricated
	Shear spinning	Eliminates longitudinal welds Permits integral reinforcements Provides good thickness control Forming can be performed hot	High cost for low production quantity Limited equipment availability Some limitations on size

technically impractical, especially where the number of units to be manufactured is too small to justify a large investment in construction of special heat-treatment facilities. Materials chosen for such tanks are required to have good properties and toughness in as-welded welds. The impact of heat-treatment requirements on material selection is discussed further in section 2.2.2.3.

Detailed information on deformation processing of various aluminum, titanium, iron, nickel, and cobalt alloys is provided in references 17 through 23.

2.2.2.2 WELDING

Material welding characteristics and weld properties are primary considerations in the selection of metals for tanks. A weldable material is one that can be fused without the formation of deleterious phases or constituents either in the fusion zone or in adjacent heated areas, has sufficient ductility (both in the bead and in adjacent areas) from the melting temperature to room temperature to resist cracking, and has suitable strength and fracture resistance either as-welded or on completion of postweld thermal processing. From the standpoint of practicality, a weldable material should also be amenable to repair welding procedures without inherent tendencies toward the formation of new defects or significant impairment of properties.

The strength of weld metal usually is lower than that of parent metal. This difference can result from a variety of causes, as follows:

- Welding alloys that obtain their strength by cold working, which cannot be performed after welding
- Filler alloys that have good ductility but lower strength than the parent metal, or that lack heat-treat response
- Lack of proper heat treatment after welding
- Lack of strength in the cast-weld deposits, even after heat treatment
- Defects both in weld metal and in weld geometry
- Increased scatter in weld properties as compared with parent metal, the result being similar average strengths but lower statistically computed design strengths for the welds.

Reduced design strengths in welds usually are compensated for by providing extra thickness in weld joint areas. Details of weld joint designs are provided in section 2.3.6.1.

Welds usually are less ductile than parent metal (although occasionally the reverse is true because of the use of ductile filler material or lack of heat treatment in the weld area) and therefore usually are less able to withstand the effects of stress or strain concentration. For this reason, welds generally are located away from areas such as abrupt changes in contour, where high local strains are likely to occur as the tank is pressurized. For the same reason, stress concentrations in the weld itself (e.g., at large unmachined beads or other geometric irregularities) are undesirable.

In the as-welded condition, welds contain residual stresses unless special welding processes or operations designed to prevent them are used. In general, the severity of such residual stresses increases with increasing material thickness and number of weld passes, low thermal conductivity, high thermal expansion, and high modulus of elasticity. On the other hand, processes such as pressure welding and forge welding may result in no significant residual stress.

It is often necessary to relieve residual stresses in tanks to prevent cracking, warpage, reduced fatigue strength, or reduced reliability against fracture in general. Tank welds usually are stress relieved during subsequent thermal processing such as aging of titanium and heat treatment of low-alloy steel. Welds in the as-welded condition have been successful in some tanks (e.g., those in large boosters or lower stages). The alloys used in these applications have relatively high ductility and good fracture toughness in the welds and adjacent material; such alloys include 2014, 2219, 6061, and 5000-series aluminum alloys, and the AISI 300-series stainless steels.

Detailed information on welding can be found in references 24 through 26.

2.2.2.3 THERMAL PROCESSING

Thermal processing procedures for alloys of interest for high-strength pressure vessels are so detailed and variable that it is not feasible to attempt more than an outline of this subject in this monograph, emphasis being given to those details that have possible impact on design and material selection. Detailed information on heat treatment can be found in references 27 through 39, or obtained from the producers of specific alloys.

Before an alloy can be selected for a proposed tank, it is necessary to determine if the thermal processing required to obtain the desired design properties can be accommodated within an economically feasible manufacturing plan. Depending on material forming, machining, and welding characteristics, on the need for postweld thermal treatment to relieve residual stresses or increase weld strength, and on the difficulty of heat treating completed components or tanks due to size, complexity, possibility of distortion, and similar considerations, thermal processing may be performed in the following phases of manufacture:

- As received or prior to any fabrication

- During or after fabrication
- After rough machining
- On welded components or completed tanks.

The important characteristics of thermal processes applicable to alloys of greatest current interest for high-strength pressure vessels are outlined in table V. (This table is intended to assist in material selection studies rather than to provide detailed processing information on specific alloys).

Annealing frequently is required prior to or during forming of tank components, either because of limitations on material ductility or limitations associated with the forming process or capacity (power) of available equipment. The annealing process indicated may either be a full anneal, as shown in table V, or a lower temperature "process anneal" (process annealing treatments were omitted from table V for the sake of simplicity). However, a full annealing treatment normally cannot be performed on an alloy that obtains strength from cold working, since the strength of such materials cannot usually be restored by any process that can be performed on completed tank components.

Several of the alloys listed in table V have considerable formability in hardened or partially-hardened conditions. These include the aluminum alloys shown (especially when not work hardened or aged to the highest strength levels); HY140, 9 nickel - 4 cobalt, and 18-nickel maraging steels; and work-hardened austenitic stainless steels (excepting full hard and harder tempers).

Many of the materials listed in table V do not require heat treatment after welding, either to restore mechanical properties or to relieve residual stress. Alloys that have been used in the as-welded condition or that have potential for such are shown with a check mark in the column "None", under the general heading, "Postweld thermal processes performed or required". Some of these alloys also have check marks in other columns, indicating that it may be necessary in some applications to thermally process the material after welding. An example of the latter category is 18-percent-nickel maraging steel, which has had limited use in the as-welded condition but which requires aging after welding to develop maximum mechanical properties in welds.

Aluminum alloys that must be formed in the as-solution-treated condition are sometimes aged after forming and are not further heat treated after welding. However, in the fabrication of large parts, aging may result in growth that is both significant and variable, and thereby produce difficulties in fitup of parts for welding. This problem occurred during fabrication of the large 2014-aluminum cylinders for the Saturn S-II stage. It was solved by contouring cylindrical sections in the T6 condition.

Table V. - Thermal Processes Applicable to the Construction of Metal Tanks

Material type: Alloy system	Material type: Hardening process	Material type: Typical weldable alloys	Thermal processes(1)	Typical temperatures for process (°F)	Atmosphere usually required(2)	Typical quenching (cooling) medium or method	Condition achieved(3)	Post weld thermal processes performed or required: None	Stress relief anneal	Age	Heat treat
ALUMINUM	Work hardening	5052, 5083, 5086, 5456	Stress relief anneal	350	Air	Air	Stress relieved	X	X		
			Full anneal	625 - 700	Air	Air	Completely soft				
	Age hardening	2014, 6061	Solution heat treat	875 - 1,000	Air	Water	Prepared for aging (moderately soft)	X			X
			Age	320 - 360	Air	Air	Heat treated				
			Stress relief anneal	Various	Air	Air	Stress relieved				
			Full anneal	750 - 800	Air	Air or slower	Completely soft				
	Cold work plus age hardening	2219	Solution treated and cold worked	As received			Moderately soft	X		X	
			Age	325 - 375	Air	Air	Heat treated				
			Stress relief anneal	300 - 350	Air	Air	Stress relieved				
TITANIUM	Nonhardening	5Al-2.5 Sn (ELI)	Stress relief anneal	1,000 - 1,200	Inert gas	Air	Stress relieved		X		
			Full anneal	1,300 - 1,450	Inert gas	Air	No work hardening				
	Age hardening	6Al-4V ELI, 6Al-4V	Solution heat treat	1,650 - 1,750	Inert gas	Water	Prepared for aging		X	X	
			Age	950 - 1,150	Inert gas	Air	Heat treated				
			Stress relief anneal	1,000 - 1,200	Inert gas	Air	Stress relieved				
			Full anneal	1,300 - 1,500	Inert gas	Slow cool	Free from hardening				
LOW-ALLOY STEEL	Martensite reaction	4130, 4340, 4335V, D6AC, 300M	Normalize	1,600 - 1,700	Controlled	Air	Prepared for heat treat		X		X
			Austenitize and quench	1,400 - 1,600	Controlled	Oil	Hard (not ductile)				
			Temper	400 - 1,200	Controlled or air	Air	Heat treated				
			Full anneal	1,450 - 1,650	Controlled	Slow cool	Softened				
ALLOY STEEL (SPECIAL CATEGORY)	Martensite reaction	HY140, 9Ni-4C_o-.20C (or .25C)	Normalize	1,600 - 1,700	Controlled	Air	Prepared for heat treat	X			
			Austenitize and quench	1,475 - 1,550	Controlled	Oil or water	Hard				
			Temper	900 - 1,100	Air	Air	Heat treated				
			Full anneal	1,100 - 1,300(4)	Controlled	Air	Moderately soft				

MARAGING STEEL	Martensite reaction plus age hardening	18-Nickel maraging	Solution treat	1,475 - 1,525	Controlled	Air	Prepared for aging (moderately soft)	X		X	
			Age	875 - 925	Air	Air	Heat treated				
			Stress relief anneal	800 - 875	Air	Air	Stress relieved				
			Full anneal	1,500 or 1,750 + 1,450	Controlled	Air	Softest condition				
STAINLESS STEEL, AUSTENITIC	Work hardening	301, 304L, 21Cr-6Ni-9Mn	Stress relief anneal	650 - 700	Air	Air	Stress relieved	X			
			Full anneal	1,800 - 2,050	Controlled or air	Water	Completely soft				
PRECIPITATION HARDENING STAINLESS STEEL	Martensite reaction plus age hardening	17-4 PH, 15-5 PH, PH 13-8 Mo	Solution treat	1,875 - 1,925	Controlled or air	Oil or water	Prepared for aging (moderately soft)			X	X
			Age	1,000 - 1,150	Air	Air	Heat treated				
			Over-age	1,450 + 1,150	Air	Air (both temperatures)	Ductile condition				
	Age hardening	AM350, AM355, PH 14-8 Mo	Austenite condition	1,700 - 1,750	Controlled or air	Air	Prepared for hardening	X	X	X	X
			Transform	-100 - +60	Air	Air	Hard (not ductile)				
			Age	850 - 1,050	Air	Air	Heat treated				
			Equalize	1,375 - 1,450	Air	Air or Oil	Pre-conditioned (AM350, 355 only)				
			Full anneal	1,800 - 1,950	Controlled or air	Air or Oil	Completely soft				
SUPER-ALLOYS	Nonhardening or work hardening	L605 (HS25), HS188	Stress relief anneal	1,200 - 1,300	Air	Air	Stress relieved	X	X		
			Full anneal	1,800 - 2,250	Controlled or air	Air	Completely soft				
	Age hardening	Inconel 718	Solution anneal	1,800 - 1,975	Controlled or air	Air or faster	Softened, prepared for aging			X	
			Age	1,200 - 1,450	Air	Air	Heat treated				
			Stress relief anneal	1,000 - 1,300	Air	Air	Stress relieved				

NOTES:

(1) Process annealing treatments, used to remove a portion of work hardening and permit further forming while avoiding the high temperatures associated with full annealing, were omitted to simplify table.

(2) Titanium alloys are sometimes thermally processed in a vacuum, or in air when a sufficient depth of metal removed all over is planned. Controlled atmospheres for steel heat treat are described in reference 28. The choice of controlled atmosphere or air depends on such factors as process temperature and time, material thickness and surface requirements, metal removed after heat treatment, etc. (A controlled atmosphere is an atmosphere of special composition employed to attain a desired environment for surface treatment or heat treatment).

(3) Conditions listed as being achieved are only approximate. For instance, the degree of residual stress relief obtained is a function of the stress relief temperature, which is often restricted by the need to avoid overaging or overtempering.

(4) Temperatures pertain to isothermal transformation annealing process. Extended-duration exposure to such temperatures is required to achieve softening.

Dimensional changes occur during heat treatment or aging of many other alloys of interest for tank construction, particularly in phase-change materials such as alloy steels and precipitation-hardening stainless steels. This factor has affected manufacturing planning and even the suitability of alloys for proposed designs.

Residual stresses that are introduced into titanium alloys and most martensitic steels (except as noted in Table V) during welding normally require thermal relief. In the case of heat-treatable titanium alloys, relief is often accomplished in a combined stress relief and aging treatment after welding. Conventional low-alloy steels must usually be fully heat treated after welding, and weld stress relief takes place during this process.

Annealing treatments to remove residual stresses resulting either from deformation processing or from welding vary appreciably according to the degree of stress relief sought, the temperatures at which loss of material hardening begins (for alloys heat treated prior to forming or welding), and on practical difficulties in heating components or assemblies. It is usually necessary to tailor such processes to specific materials and applications, and such detailed information is beyond the scope of this monograph.

Table V indicates the types of alloys that require high temperatures, special atmospheres, or rapid quenching during heat-treatment processes preparatory to hardening. Such processes are difficult and costly to perform on completed components, especially in large sizes. Special furnaces, fixturing, handling, and quenching facilities that may be required may not be economically justified by the number of tanks to be fabricated.

2.2.3 Material Compatibility with Environments

Materials selected for liquid rocket system tanks must be compatible with the fluids to be contained. Alone or in combination with a suitable protective finish, tank materials must also be resistant to the effects of exposure to all external environments encountered. In addition, the contamination or deterioration of tank materials during material processing, manufacturing, inspection, test, transportation, and storage must be prevented by avoiding exposure to or providing protection from all fluids or processes that are known to have deleterious effects. The undesirable metal/fluid reactions, the possible consequences, and the major sources of such reactions are summarized in table VI.

Metal/fluid incompatibility reactions are discussed in the following sections, first from the standpoint of the major sources of reactions that must be avoided, and second from the standpoint of specific failure mechanisms and their avoidance.

Table VI. – Causes and Effects of Metal/Fluid Reactions

Metal/Fluid reaction	Possible consequences to system	Major sources of metal/fluid reaction			
		A	B	C	D
Metal corrosion (including general corrosion, pitting, intergranular corrosion, and chemical attack)	(1) Metal weakening through loss in cross-sectional area and introduction of stress raisers (2) System contamination with corrosion products	X	X	X	X
Catalytic decomposition of propellants	Loss of efficiency or contamination of system or both			X	
Hydrogen embrittlement of steel	Brittle fracture at low stresses, especially under long-duration loading	X			
Contamination of titanium	Brittle fracture at low stresses	X	X	X	X
Stress corrosion	Metal crack growth or fracture at reduced stress levels	X	X	X	X
Galvanic corrosion	(1) Rapid deterioration of material (2) Stress-corrosion failure	X	X	X	X
Hydrogen-environment embrittlement of metals	Embrittled behavior of metal while exposed to hydrogen gas			X	
Ignition of materials	Catastrophic combustion			X	

Notes:
A = manufacturing fluids and processes
B = proof and system testing
C = service fluid containment
D = atmospheric exposure

2.2.3.1 SOURCES OF MATERIAL/FLUID REACTIONS

2.2.3.1.1 Manufacturing Fluids and Processes

Many high-strength alloys are susceptible to attack or contamination by rather commonly used manufacturing fluids and processes. Some of the potential sources of such reactions are lubricants; cleaning agents, solvents, or baths; etching, descaling, stripping, or brightening solutions; identification marking materials; nondestructive inspection fluids; electrolytic and electroless plating operations; electrolytic metal removal or cleaning processes; chemical milling; electrical discharge machining; heat treatment and welding. These materials and processes are not to be condemned *per se*; however, they have been sources of undesirable reactions and may require verification of compatibility before being used in a new application.

Of the alloys of interest for tank construction, titanium alloys are the most susceptible to contamination. Most of the categories of materials and processes listed above are potential sources of trouble for titanium. The most frequently occurring mechanisms of titanium contamination during manufacturing operations are as follows:

- Hydrogen contamination from room-temperature processes or from contact with hydrogen (or gases that contain the element hydrogen) at high temperatures

- Oxygen and nitrogen contamination from contact with these gases (as in air) at high temperatures

- Halogen contamination from the use of halide-containing materials on titanium prior to heat treatment or welding.

Hydrogen contamination embrittles titanium when concentrations exceed about 100 to 150 parts per million, the effective concentration depending on the type of alloy; the subject of hydrogen in titanium is treated in references 31 and 32. Oxygen and nitrogen also tend to embrittle titanium. The depth of embrittlement resulting from heat treatment in air is such that it is often removable by machining. However, when titanium alloys are welded in air, the entire weld is embrittled. The subject of titanium oxidation and contamination is treated in reference 33. A listing of materials and processes found to be compatible with titanium alloys is provided in reference 34, together with a list of substances that have proven to be incompatible.

The embrittlement of steel by internal contamination with hydrogen has been well documented; and current procedures for production, processing, and manufacturing of steel reflect the need to prevent embrittlement by avoiding the sources of such contamination or by removing the contaminant if it cannot be avoided. Typical sources of contamination are electrolytic processes such as electroplating and cathodic cleaning; electroless plating, pickling, and acid-stripping baths; chemical milling; and heat treating or welding in atmospheres contaminated with hydrogen or water.

The susceptibility of steels to hydrogen embrittlement increases with increasing strength level. High-strength, low-alloy steels are the most susceptible to the effects of hydrogen; however, it may be assumed that all steels of interest in the present context excepting austenitic stainless steel (AISI 300 series) are to some degree affected. In reference 35 (a user specification for the prevention and elimination of hydrogen embrittlement in steel), process control is indicated for all alloy steels over 140 ksi (tensile strength), all precipitation-hardening stainless steels above 160 ksi, all martensitic stainless steels above 180 ksi, case-hardening steels, carbon and alloy spring steels, and tool steels. The subject of embrittlement of steel by hydrogen contamination is treated in considerable detail in references 36, 37, and 38.

Other types of alloys of interest for liquid rocket tanks and components, viz., aluminum alloys and nickel- and cobalt-base high-temperature alloys, are not susceptible to hydrogen-contamination embrittlement. However, such alloys may exhibit a surface-related brittleness during exposure to gaseous hydrogen at temperatures near ambient temperature, as discussed in section 2.2.3.2.3. This latter phenomenon is distinguished from the embrittlement of titanium and steel via internal contamination.

2.2.3.1.2 Testing Fluids

Fluids used in tank and system testing are a potential source of reactions with tank materials; these fluids therefore must be properly evaluated before use and properly controlled in use. Although such fluids usually are not corrosive in nature, their formulation must be properly chosen and any contamination avoided so that local attack that can nucleate fracture at a lowered pressure may be prevented. However, the most noteworthy consequences of incompatible testing fluids have been instances of stress corrosion (sec. 2.2.3.2.1) or reduced threshold stress intensities for crack growth (sec. 2.2.4.1). Examples are the premature failure of titanium tanks pressurized with methanol and of steel tanks pressurized with water (refs. 39 and 40, resp.).

2.2.3.1.3 Stored Fluids

Liquid propellants, particularly oxidizers, often possess a highly aggressive or reactive chemical nature. The containment of such substances with metals that also may be quite reactive often is possible only because of the protective mechanism of the formulation of a relatively stable oxide film or layer on the metal surface. Because of the inherent potential reactivity, it is often difficult to predict the circumstances under which metals will resist such aggressive fluids or, alternatively, will be rapidly attacked, or will fail from stress corrosion or some other failure mechanism. For this reason, it has been found necessary to verify the compatibility of proposed metal/fluid combinations under conditions that represent those anticipated in service, particularly the factors of chemical composition (including suspected fluid contaminants), temperature, and duration of exposure. Exposure stress is also important, as indicated in section 2.2.3.2.1. Exposure pressure may or may not be important. The effects of a fluid on crack growth should also be considered, as discussed in section 2.2.4.1.

Besides composition, the materials-oriented factors affecting the rate of attack or degree of incompatibility include heat-treat condition, existence of cold work or residual stresses at exposed surfaces, and exposure of metal end grain (which often results in much greater attack than exposure of the other grain dimensions). Also, welds may be affected in an entirely different manner from the parent (unwelded) metal because of changes in chemistry and structure during welding.

Propellant decomposition may be accelerated by the catalytic effects of certain metals. In the selection of materials, this possibility usually is investigated, particularly for metals used in contact with hydrogen peroxide and hydrazine-type propellants.

Considerable data on the compatibility of various metals and nonmetals with a number of different liquid rocket fuels and oxidizers are available in references 42 and 43. Reference 43 contains a summary of data on corrosive attack rates, the occurrence of propellant catalytic decomposition, and impact ignition. Additional discussion of material failure mechanisms resulting from reactions with stored fluids is contained in section 2.2.3.2.

2.2.3.1.4 Atmospheric and Environmental Corrosion

Integral tanks that form a portion of the exterior surface of a vehicle usually are subjected to direct atmospheric exposure during a portion of the vehicle life. However, vessels that are not so exposed after system installation in the vehicle usually are exposed indirectly to corrosive atmospheric conditions, principally moisture-laden air with or without the contributing effects of salt or industrial chemicals. Such exposure occurs during manufacturing, storage, testing, transportation, and vehicle operation.

Some alloys are quite resistant to atmospheric corrosion because of the formation of a thin, tightly adherent, protective oxide film. Titanium; the high-nickel, high-chromium stainless steels and superalloys; and some aluminum alloys are in this category. However, many other high-strength alloys of interest for liquid rocket tanks and associated hardware (e.g., 2000-series aluminum alloys and low-alloy steels) must be provided with a protective finish.

References 43, 44, and 45 often are used as sources of information on the selection of metal finishes for spacecraft hardware. Table II of reference 43 provides a convenient guide to the alloys that normally need a finish for corrosion protection. However, specific space vehicles usually have requirements that are likely to differ from those envisioned in such general specifications. Such requirements may include operation in a hard vacuum, thermal control in space, and identification, for example. For this reason, finish requirements are usually defined and documented for specific space vehicles. Examples of this are the finish specifications prepared for the Apollo spacecraft and the Saturn S-II stage (refs. 46 and 47, resp.).

The choice of materials and finishes must also consider the possibility of stress corrosion or galvanic corrosion in atmospheric environments. These failure mechanisms are treated in the following sections.

2.2.3.2 TYPES OF MATERIAL/FLUID REACTIONS

This section treats failure mechanisms involving material reactions with fluid environments encountered in service applications; these phenomena must be considered in the design and selection of materials for liquid propulsion systems.

2.2.3.2.1 Stress-Corrosion Cracking

Stress-corrosion cracking is one of the more common sources of failure of highly stressed metals. This form of cracking may be defined as delayed fracture resulting from the combined action of stress and a corrosive environment. Since stress corrosion can occur in environments that produce little or no ordinary corrosion, the term "aggressive environment" often is used to denote environments that react unfavorably with some metals or are suspected of doing so. Corrosive or aggressive environments to which liquid propulsion system tanks and associated hardware are exposed may be either a fluid contained in the tank (during testing or in service) or an external environment. The most common external environment is ambient air containing moisture and traces of salt and other chemicals.

The occurrence of stress corrosion depends on three basic factors: the severity of the environment for the particular material, the severity of the sustained stress, and the duration of exposure. Therefore, avoiding this type of failure requires (1) avoiding metal exposure to aggressive environments or selecting materials that are resistant to such environments, (2) minimizing the severity of sustained tensile stresses at exposed metal surfaces, and (3) (if possible) minimizing exposure duration.

The subject of stress-corrosion cracking and its prevention (especially in military equipment) is treated in military handbook MIL-HDBK-724 (ref. 48); table I in this reference provides a convenient listing of alloys and associated environments for which stress-corrosion cracking has been reported. Stress-corrosion data on a variety of alloys and environments may be found in reference 49; table 1.1 of this reference also contains a relatively comprehensive listing of alloy families and corrosive materials for which stress-corrosion cracking has been observed. In addition to these two sources of data, reference 50 is a valuable collection of data on stress corrosion of titanium. This reference covers the corrosive effects of molten alloys such as cadmium and also the reaction between solid silver and silver chloride in contact with titanium at temperatures above or about 600° F. A more complete listing of low-melting-point metals that may not be used in contact with titanium at elevated temperatures is provided in reference 34 (table VII).

Titanium stress corrosion with nitric oxide (NO)-free N_2O_4 and also with methyl alcohol during the Apollo program are documented in reference 39. This reference also contains the results of compatibility testing of many other materials in contact with titanium. The titanium/N_2O_4 incompatibility problem was solved for the Apollo program by maintaining a sufficient NO content to inhibit the reaction between titanium and N_2O_4. Specification NASA MSC PPD-2 for propellant grade N_2O_4 (ref. 51) currently specifies NO content at 0.60 to 1.00 percent.

The incompatibility of titanium and titanium alloys with the fluorocarbon solvent Freon MF (trichlorofluoromethane) is treated in reference 52. Indications of titanium incompatibility with the products of a reaction between small amounts of the solvent Freon TF (trifluorotrichloromethane) and hydrazine (N_2H_4) are discussed in reference 53.

Many high-strength alloys of interest for tank construction are subject to stress-corrosion cracking in atmospheric environments. Many aluminum alloys in the 2000 and 7000 series are susceptible, some at quite low levels of sustained stress, the response depending on material heat-treat condition and direction of the stress with respect to the material grain direction. Conventional low-alloy steels are also susceptible, especialy when heat treated to high strength levels. Precipitation-hardening stainless steels vary, as a group, in resistance to this failure mode. Some of these materials are quite sensitive and others quite resistant. Titanium alloys normally resist atmospheric effects, but are susceptible to salt and other chlorine sources that remain in contact with the metal at temperatures above about 550° F. Some titanium alloys have also been found to be sensitive to sea water at room temperatures. A comparison of the resistance of various alloys to stress corrosion in atmosphere and other natural or simulated natural environments is provided in table VII.

The use of protective finishes and coatings to prevent stress corrosion failures of metals during exposure to natural environments generally has not met with success when there existed a pronounced susceptibility to this failure mode. This has been indicated by service experience with aluminum alloys 7075-T6 and 7079-T6 and by tests performed to evaluate the effectiveness of various coatings for the protection of high-strength steel from stress corrosion (ref. 54).

Currently two distinct approaches are being used to evaluate the effects of stress in corrosive environments. One might be called the smooth-specimen or conventional-testing approach and the other, the fracture-mechanics approach. Conventional testing techniques, which involve exposure of specimens stressed either in bending or in direct tension, are described in reference 49 (ch. 12). The fracture-mechanics approach involves exposing precracked

Table VII. – Comparison of the Resistance of Various Alloys to Stress-Corrosion Cracking in Natural Environments[1]

Alloy system	Alloy	Heat treat condition	Exposure conditions	Direction of loading[2]	Stress-corrosion susceptibility: Estimated maximum sustaining stress for no failure[3], ksi	Stress-corrosion susceptibility: Appraisal	Reference[4]
Al-Cu (wrought plate)	2014	T6	3½% NaCl solution for 30 days	L LT ST	45 30 <8	Very susceptible	8
	2024	T3, T4		L LT ST	35 20 <8	Very susceptible	
	2024	T8		L LT ST	>50 >50 39	Susceptible	
	2219	T8		L LT ST	40 (5) 38 (5) 38 (5)	Mildly susceptible	
Al-Zn (wrought	7075	T6	3½% NaCl solution for 30 days	L LT ST	50 45 <8	Very susceptible	
	7075	T76		L LT ST	49 (5) 49 (5) 25	Susceptible	
	7075	T73		L LT ST	50 48 (5) 43 (5),(6)	Susceptible only at thicknesses over 3.00 in	
	7079	T6		L LT ST	55 (5) 42 <8	Very susceptible	
Titanium	(General)	–	Atmosphere (including marine and industrial)	–	–	Not susceptible	
	5Al-2.5Sn	Annealed	Sea water	–	<60	Susceptible	50
	Alpha-beta alloys	Annealed	Sea water	–		Some susceptibility depending on composition	50, 61, 62
	(General)	–	NaCl or other halide-containing material remaining in contact at temperatures above about 550° F[7]	–		Susceptible	61, 62

(continued)

Table VII. – Comparison of the Resistance of Various Alloys to Stress-Corrosion Cracking in Natural Environments[1] (concluded)

Alloy system	Alloy	Heat treat condition	Exposure conditions	Direction of loading[2]	Stress-corrosion susceptibility: Estimated maximum sustaining stress for no failure[3], ksi	Stress-corrosion susceptibility: Appraisal	Reference[4]
Alloy steel	4130, 4340, 4335V, D6Ac, 300M and similar high strength low alloy steels	Yield strength above 150 ksi	Atmosphere (including marine and industrial)		80	Susceptible	49
	9Ni – 4Co – 0.20C (or 0.25C), 18-Ni maraging		Atmosphere (including marine) and industrial)			Susceptible but superior to low-alloy steel at equivalent strength levels	49, 55
Austenitic stainless steel	AISI 300 series	Annealed or work hardened	Atmosphere (including marine and industrial)	–	–	Not susceptible	49, 60
			Chloride - containing solutions, heated above ambient temperatures	–		Susceptible	59, 60
Precipitation hardening stainless steel	17-4 PH[8]	Yield strength above 115 ksi	Atmosphere (including marine and industrial)	–	100	Susceptible	56
		Yield strength 115 ksi or less	Atmosphere (including marine and industrial)	–	90 percent of minimum	Mildly susceptible	
	AM350, AM355	SCT 850	Marine atmospheres and salt spray test environments	–	50	Very susceptible	49, 56
		SCT 1000	Marine atmospheres and salt spray test environments			Susceptible (less so than in SCT 850 condition)	49
	PH15-7Mo	RH 950	Marine atmospheres		65	Susceptible	56
		RH 1050	Marine atmospheres	–	85	Susceptible	
	PH14-8Mo	RH 1050	Marine atmospheres	–	>115	Mildly susceptible	57
Nickel-base super alloy	Inconel 718	Age hardening	Synthetic sea water and salt spray test environment	–	–	Not susceptible	58

Notes

(1) This table provides estimates of the comparative resistance of materials to stress-corrosion cracking when exposed to fluids and chemicals that may be encountered in natural environments; it is not intended to cover the full range of fluids with which the materials may react but which are not usually encountered in natural environments.

(2) Loading direction is given with reference to material grain direction: L = longitudinal; LT = long transverse; ST = short transverse. Absence of symbol means that no specific data on loading direction is available.

(3) Estimated highest sustained tensile stress that will not result in stress-corrosion cracking in originally smooth specimens; does not account for the possible effects of stress concentrations or indicate the relative performance of precracked specimens.

(4) Numbers refer to entries in reference list.

(5) Highest stress at which tests were conducted. No failures observed.

(6) Up to 3.00 in. thick. At greater thicknesses, the comparable value for the short transverse direction should be 75 percent of the guaranteed yield strength.

(7) Even minor sources of chlorine such as the salt from a fingerprint or chlorine from a tap water rinse should not remain in contact with titanium during heat treatment or other elevated temperature processes.

(8) 15-5PH and PH13-8Mo are estimated to be equal or superior to 17-4PH in resistance to stress-corrosion when heat treated to equivalent strength levels.

specimens to the test environment. In such tests, the load level and the crack length combine to produce a local stress intensity that must be less than that which causes crack growth in dry air (or other nonreactive reference environment) but still high enough to reveal any environment-caused promotion of crack growth. This method of testing is discussed in section 2.2.4.1 and is described in detail in reference 63.

The fracture-mechanics approach often is a much more sensitive indicator of stress/environment effects; it can show significant reductions in material resistance to crack growth in media for which no stress-corrosion effect is observed in conventional tests. Values for threshold stress intensity are also required for the implementation of a fracture-mechanics-based safe-life analysis as discussed in section 2.2.4.2 of this monograph.

2.2.3.2.2 Galvanic Corrosion

The exposure of electrically connected dissimilar metals to an electrolyte results in generation of an electric current and rapid attack on the "less noble" of the two metals. The metal dissimilarity that provides the driving force for such reactions is dissimilarity in the electrode potential developed by each of the two metals when in contact with the fluid. The circuit must be completed by the electrical conductivity of the fluid in which the two metals are immersed and also by electrical contact between the two metals or electrodes. (The latter path is analogous to "shorting out" the terminals of a battery.) The greater the electrode potential difference, and the more conductive the current paths, the more rapid will be the attack.

Galvanic action is present in many corrosion processes that do not appear to involve dissimilar metals. In such cases, the dissimilarity may be between metal phases in the microstructure or between metal grain boundary areas and the metal grain, or it may be a concentration gradient in the solution, which results in different electrode potentials in different areas on the same piece of metal. However, these processes are included under the category of corrosion, and the present concern is with the gross form of galvanic corrosion that results from improper use of dissimilar metals.

Galvanic corrosion can occur within a system in which an electrically conductive fluid is stored; it may occur outside the system as a result of the effects of atmospheric moisture. Within a system, the distances spanned by such effects can be as long as the electrical paths provided by the fluids on the one hand and the metal circuit on the other. Metal dissimilarities may occur between the tank material and metals used for internal design details such as slosh baffles, reservoirs, filters, and screens. Exterior to the system, galvanic action usually is limited to metals that are in contact, in very close proximity, or in the same moisture trap, if such exists.

Within liquid propellant systems, corrosion of dissimilar metals frequently is of little or no concern because most propellants either have little electrical conductivity or do not develop significant electrode potentials in contact with normal structural metals or both. However, the possibility exists that new or inadequately tested propellants will be capable of supporting or promoting galvanic action either alone or together with contaminants. Also, galvanic corrosion can readily occur within fluid propulsion systems during procedures in which liquids other than propellants (particularly water) are in contact with galvanically dissimilar metals.

The permissible and undesirable combinations of metals from the standpoint of galvanic corrosion in the atmosphere or in aqueous solutions are given in references 44 and 45; the anodic member of each combination also is indicated. Additional and more detailed data on the susceptibility of dissimilar metals to galvanic corrosion in solutions of varying pH are provided in reference 64. (It should be noted that galvanic electrode potentials determined using aqueous solutions are not valid for nonaqueous solutions.)

Protective coatings sometimes are used to prevent galvanic action when it is desired to use dissimilar metals in a way that might be conducive to galvanic corrosion. However, coatings improperly used can worsen the situation. For instance, when the anodic member of a dissimilar pair is the only member coated, a small coating defect results in a very small anode facing a large cathode; rapid attack results from a low ratio of anode-to-cathode area. Also, platings that are cathodic with respect to the substrate metal can cause accelerated attack at local plating defects.

2.2.3.2.3 Hydrogen-Environment Embrittlement

It has been observed recently that for many metals the tensile strength, notched tensile strength, fatigue strength, resistance to crack growth, and ductility are decreased, sometimes seriously, when the metal is tested in a hydrogen-gas environment. This phenomenon differs significantly from the phenomena of hydrogen-contamination embrittlement of steel and of titanium alloys discussed in section 2.2.3.1.1. Embrittlement in hydrogen-gas environment appears to be a surface-related phenomenon that (with the possible exception of titanium alloys) persists only while the material surface actually is exposed to the hydrogen gas. A large number of different metals have shown such effects, and, in fact, only a few materials of interest for tank construction have been found to be essentially free from this phenomenon.

The reductions in strength, toughness, and ductility of metals have occurred during hydrogen exposure both at room temperature and at moderately depressed and moderately elevated temperatures. The effects have been observed at one atmosphere of pressure, but are more noticeable with increased gas pressure. The greatest effects have occurred in metals that had been heat treated to maximum strength levels. High-purity hydrogen normally is used in laboratory investigations of hydrogen embrittlement; however, the number of instances of rapid crack growth in steel hydrogen-storage systems now attributed to this embrittlement indicates that it is a real problem for systems that contain gaseous hydrogen.

This phenomenon is treated in detail in references 65 through 68; considerable useful data are provided therein on alloys of interest for tank construction. Service experience, in which rapid growth of cracks in low-carbon steel and 400-series stainless steel was encountered in gaseous-hydrogen storage systems, is described in reference 69.

Titanium and titanium alloys appear to be a special case of the effects of hydrogen exposure at room temperatures. Exposure to hydrogen gas can produce both the environmental effects described above that do not persist after the exposure and, with exposure of sufficiently long duration, embrittlement that goes beyond the surface and remains after the exposure. The latter mechanism of embrittlement actually is one of internal contamination and formation of hydrides. No other alloy system of interest for tank construction has shown any evidence of internal contamination resulting from room-temperature exposure to hydrogen gas. Titanium contamination with hydrogen gas at temperatures near room temperature is treated in references 70 through 73.

2.2.3.2.4 Material Ignition

The susceptibility of titanium to potentially catastrophic ignition under conditions of impact or other instances of localized high-energy pulses in the presence of strong oxidizers now is widely known. This phenomenon was first observed in red fuming nitric acid (RFNA) and liquid oxygen (LOX). Reactions also have been observed in liquid fluorine and in mixtures of liquid fluorine and liquid oxygen (FLOX), and in pure gaseous oxygen at pressures on the order of four atmospheres and greater. Nitrogen tetroxide (N_2O_4) has also shown a tendency toward such ignition reactions with titanium, but such reactions have been nonpropagating in nature. (The more serious problem of stress corrosion of titanium when it is exposed to nitrous oxide - free N_2O_4 was discussed briefly in section 2.2.3.2.1.) The reactions observed with liquid fluorine have also been nonpropagating rather than catastropic in nature. Further information on titanium pyrophoric reactions with fuming nitric acid, liquid oxygen, and gaseous oxygen may be found in references 74 through 77.

The method for determining material sensitivity to impact ignition usually involves a drop-weight device such as the ABMA apparatus indicated in reference 78. There should be no evidence of a reaction during twenty successive impacts of a hardened steel striker, each strike at 72 ft-lbf impact energy. Indications of a reaction are an audible explosion, a visible flash in a darkened room, or post-test evidence of discoloration or burning.

Additional information on LOX compatibility testing procedures may be found in reference 79. A large number of nonmetallic materials, particularly organic materials, also are incompatible with strong oxidizers because of the possibility of ignition. Impact may or may not be required to set off such reactions.

Undesirable or hazardous reactions also may occur between propellants in the hydrazine family and copper, lead, zinc, molybdenum (and alloys having a significant molybdenum content), and plain carbon and low-alloy steel.

The above instances do not cover this area of concern completely. The compatibility of each new material/propellant combination must be determined. Considerable data on ignition and other incompatibility reactions between various materials and propellants are available in references 41 and 42.

2.2.4 Fracture Control

The rapid development of linear-elastic fracture mechanics has provided pressure-vessel designers with a new tool to help solve the problem of unexpected brittle failures at stress levels less than the material yield strength. Previous methods for evaluating material resistance to brittle failures, such as Charpy impact strength or notched/unnotched tensile strength, primarily are used qualitatively, whereas the fracture-mechanics approach permits quantitative evaluations.

This approach, based on the fact that flaws of various sizes exist in all materials, required the development of a mathematical model for the growth of such flaws under stress in materials that exhibit both elastic and plastic behavior. This mathematical model treats the flaw as a crack and provides quantitative relationships among the crack dimensions, the applied gross section stress, and the stress intensity at the tip of the crack. Extension of the crack is dependent upon the stress intensity at its tip. The stress intensity factor, K, around the perimeter of a buried elliptical sharp crack in an infinite elastic solid under uniform normal tensile stress, σ, is described by the expression

$$K = \sigma\sqrt{\pi a/\phi^2}\ \left\{\sin^2 \beta + (a/c)^2 \cos^2 \beta\right\}^{1/4} \tag{2}$$

where β (the angle designating the location of K along the crack front), a, and c are defined as shown in figure 3 (ref. 3).

The shape factor ϕ is expressed by

$$\phi = \int_0^{\pi/2} \sqrt{1 - k^2 \sin^2 \theta}\, d\theta; \quad k = \sqrt{1 - a^2/c^2} \text{ for } c > a \tag{3}$$

Values of ϕ, the complete elliptic integral of the second kind, are published in mathematical handbooks. A very useful expression developed by Rawe (ref. 80) for approximating ϕ^2 is

$$\phi^2 = 1 + 4.593\,(a/2c)^{1.65} \tag{4}$$

This expression is known to be accurate for flaw aspect ratios (a/2c) between 0.05 and 0.5.

Irwin (ref. 81) adapted the expression given by equation (2) to the case of the part-through surface crack under uniform tensile stress by applying a multiplying factor of about 1.1.

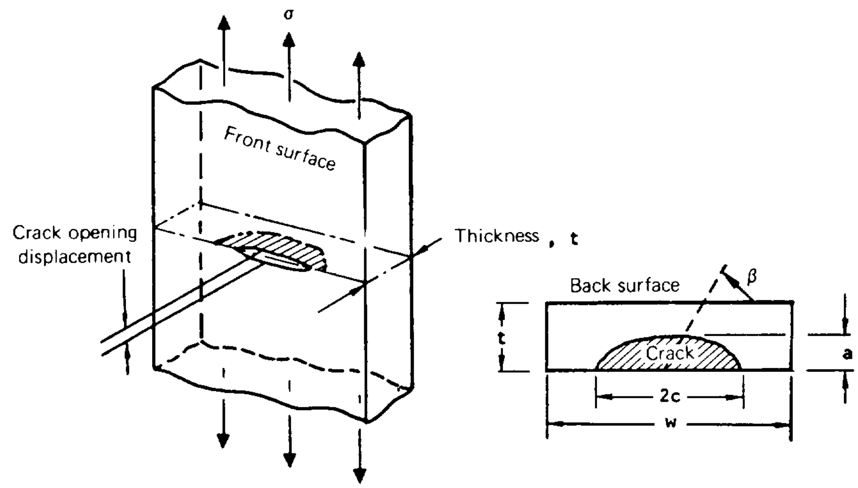


Figure 3. – Sketch illustrating surface-crack model and nomenclature used in fracture-mechanics analysis (ref. 3).

This factor was originally meant to represent the combined effects of both the front and back free surfaces being made free from normal shear stresses. For the surface flaw in the depth direction ($\beta = 90°$), equation (2) then can be rewritten as

$$K = 1.1\,\sigma\sqrt{\pi a/\phi^2} \tag{5}$$

Irwin also proposed adding an estimate of the size of the plastic zone ahead of the crack tip to the crack size. Adding the estimated plastic zone radius r_y to the crack depth a gives, for the surface flaw in the depth direction,

$$K = \frac{1.1\,\sigma}{\phi}\sqrt{\pi(2 + r_y)} \tag{6}$$

For plane-strain conditions, r_y is estimated from

$$r_y = \frac{1}{4\sqrt{2}\pi}\,(K/\sigma_{ys})^2 \tag{7}$$

where σ_{ys} is material yield strength.

Substituting equation (7) into equation (6) and solving for K then gives

$$K = 1.1\,\sigma\sqrt{\pi a}\Big/\sqrt{\phi^2 - 0.212\,(\sigma/\sigma_{ys})^2} \tag{8}$$

The expression under the radical in the denominator is identified as Q (the Irwin flaw shape and plasticity factor), and equation (8) then reduces to

$$K = 1.1\, \sigma \sqrt{\pi a/Q} \tag{9}$$

It should be noted that the quantity 0.212 results from $(1.1)^2/(4\sqrt{2})$ and that with consideration of more exact free-surface factors, the value of the expression will change.

Measurements of material plane-strain fracture toughness frequently are made with a specimen such as that shown in figure 3, the dimensions having the relationships

$$a \leq t/2$$

$$2c \leq w/3$$

$$w \geq 6/t$$

Additional requirements for plane-strain fracture-toughness testing are provided in reference 82.

Plots of ϕ^2 and Q as a function of a/2c (ref. 83, p. 102) permit easy evaluation of K when the applied stress and crack dimensions are known. Additional modifications to the stress-intensity expression that provide for specific geometry effects not covered by equation (2) are covered in references 4 and 83.

The stress-intensity concept has been demonstrated to apply to subcritical (stable) as well as critical (unstable) crack growth, thus providing a means for correlating the effects of stress and crack dimensions for cyclic crack growth and sustained-load crack growth. The characteristics of critical and subcritical crack growth in several widely used materials have been extensively investigated. Such data are available in references 84, 85, and 86. The application of the stress-intensity parameter to tank fracture-control procedure is treated in references 2, 3, and 4.

Fracture-mechanics techniques, when properly integrated into a total fracture-control plan, can provide the desired level of structural reliability. Such a fracture-control plan for a liquid propulsion system tank includes the following elements:

- Material selection for adequate fracture toughness, in parent metal (unwelded) and welds, under all anticipated conditions of loading and environmental exposure

- Safe-life analysis based on fracture mechanics

- Quality-control procedures for ensuring both material toughness and detection of cracks or crack-like flaws

- Application of fracture mechanics to qualification testing of tanks
- Documentation of all information and events pertinent to tank performance.

2.2.4.1 MATERIAL FRACTURE TOUGHNESS

A fracture-mechanics variable important to the initial material selection is the value of the crack-tip stress-intensity factor K required to initiate unstable crack growth in a particular material. For a specific material, and for equal conditions of constraint at the crack tip, unstable crack growth usually is initiated at a specific value of K; this critical value K_c has been designated as the material fracture toughness. For cracks in thick sections, where maximum constraint (full plane-strain condition) is developed, this parameter has been designated K_{Ic}, the plane-strain fracture toughness. This toughness parameter, which applies to tension loading normal to the crack surface, is presumed to be a material constant. When constraint at the crack tip is lacking, a plane-stress condition exists. In many applications, the degree of material constraint at the crack tip is somewhere between two cases, and the crack extension occurs under conditions described as "mixed mode".

The evaluation of materials for tanks on the basis of fracture toughness is based on test data that represent the specific application. Usually this evaluation requires a series of fracture tests of precracked specimens with surface flaws (cracks) of varying depths; specimen thickness is equal to that of the intended application. A high level of material toughness is desirable; however, the proper material choice involves the relationship of the factors of material conventional strength, density, and toughness. Figure 4 (adapted from ref. 87) shows the interaction of these parameters and the region of optimum choices. The "upper bound" of figure 4 represents the maximum K_{Ic} values observed for various material strength levels, as corrected for material density. The $K_{Ic}/\sigma_{ys} = 0.25$ line represents an attempt to arrive at minimum practical values of fracture toughness, below which the tolerable flaw sizes may become impractically small from the standpoints of manufacturing capabilities and the ability to detect the flaws during nondestructive inspection (NDI) as discussed in the following paragraph. The material choice must also take into account the effects of anticipated environments on the material resistance to crack growth, and the crack growth characteristics under cyclic loading conditions; these subjects are discussed further in succeeding paragraphs.

When a tentative material selection has been made, and material operating stress, thickness, and toughness determined, the critical crack size can be calculated by the use of the appropriate equation from reference 88. Normally, the material stress associated with this calculation is the proof stress rather than the operating stress. (Determination of the proof-stress level is treated in section 2.2.4.2.) The critical crack size determined in this manner is the size that is associated with the avoidance of failure during proof testing. The resulting critical crack size provides a rational basis for assessing the sensitivity of NDI

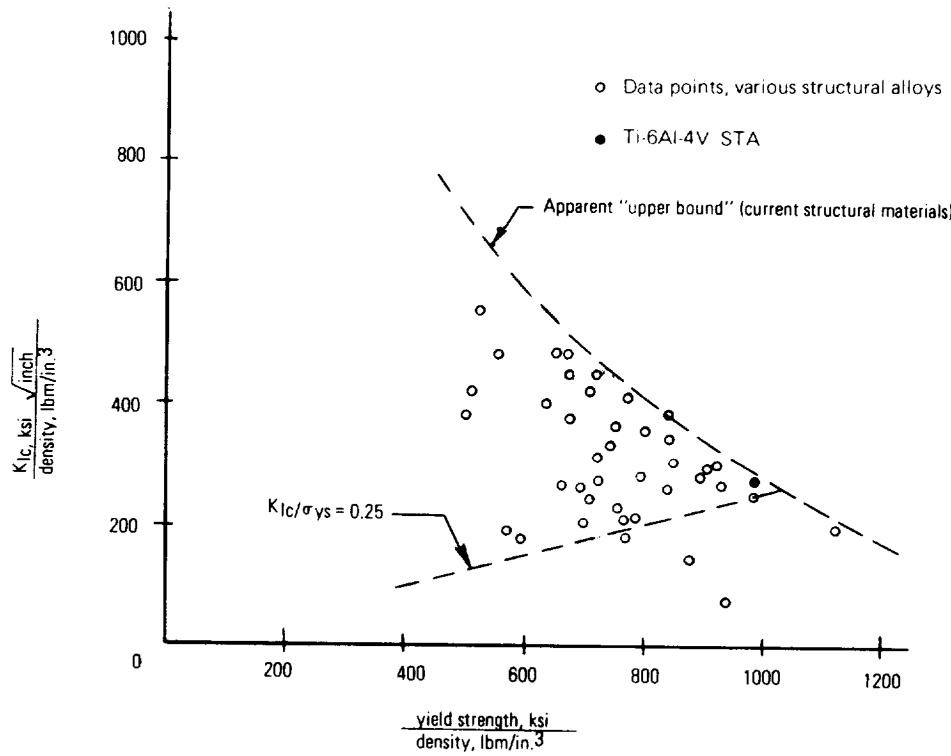


Figure 4. – Material fracture toughness vs yield strength, density normalized (adapted from ref. 87).

techniques and helps to establish the overall manufacturing and acceptance NDI requirements. The computed critical crack size may be found to be impractically small. A critical crack size smaller than the sensitivity of the available NDI facilities would increase the likelihood of tank failure during proof testing. Also, a critical crack size much smaller than the potential cracks resulting from manufacturing processes could result in excessive rejects during manufacturing and acceptance test. In such cases, the critical crack size is increased either by choosing an alternate material having a higher ratio of fracture-toughness to strength or by utilizing a lower operating stress level with the same material.

Another toughness criterion sometimes used in material selection is the "leak-before-burst" criterion. Usually it is desirable that tank failure be evidenced by leakage without rupture. This condition requires that cracks that penetrate the tank wall do so without reaching the critical size for unstable propagation. Tank designs frequently are assumed to possess the leak-before-burst characteristic when the calculated critical crack size exceeds the material thickness by an artibrary factor, which may range between one and four. However, the reliability of this assumption is uncertain and varies because materials vary in behavior as the crack nears complete penetration. The plane-stress condition that normally exists as the crack approaches a free surface permits many materials to undergo considerable increases in plastic deformation prior to separation. With such materials, if the critical crack size a_{cr} is just equal to or only slightly greater than the material thickness t, leak without burst may not occur. Investigation is required to determine the extra allowance in critical crack size (amount by which a_{cr} should exceed t) to obtain reliable leak-before-burst performance. It should also be noted that the relative advantage of leak before burst behavior is somewhat lessened when the fluid contained is hazardous if released.

Fracture-toughness evaluations performed for the purpose of selecting materials usually take into account the effects on material toughness of the temperatures anticipated in testing and service. Materials that are selected are more completely evaluated, consideration being given to potential effects of all important material variables such as material form, size, directional characteristics, cleanliness, chemical content, thermal processing and deformation processing. These factors can have considerable effect on fracture behavior. In addition, material characteristics for subcritical crack growth due to sustained loading in fluid environments and to cyclic loading must be evaluated before a tank safe-life analysis (sec. 2.2.4.2) can be performed.

Environmental Effects

As noted previously, the effects of fluid environment on crack-growth resistance are determined by loading precracked specimens in the specific fluid environments under investigation. For most specimen configurations, the initially applied stress-intensity value is kept below the value that will result in sustained-load growth in an inert reference environment. The highest stress intensity for which there is no crack growth during a sufficiently long loading period is termed the "material threshold stress intensity" for the particular medium and is designated K_{TH}. This value of the stress intensity is used to determine the initial crack size that will grow (and therefore potentially cause failure) in a particular fluid at a given level of stress. An alternate and more rapid approach for determining the threshold stress intensity for crack growth in a particular medium makes use of a wedge-force-loaded specimen in which the stress intensity decreases with increasing crack length. In this approach, a single specimen indicates the stress intensity at which arrest of growth takes place. Tests comparing the threshold stress intensity for crack-growth initiation in conventionally loaded specimens with that for crack arrest in wedge-force-loaded specimens of the same material and exposure medium have resulted in good agreement. Comparative data of that type are reported in reference 89. A collection of data on threshold stress intensities for crack growth in several tankage materials when exposed to various fluids, as compared with their respective nominal K_{Ic} values, is provided in reference 4 (p. 21).

Cyclic Crack Growth

The application of fracture-mechanics technology to the problem of crack growth under cyclic or fatigue loading has provided useful generalized analytical relationships by which the effects of loading spectra on the growth of cracks in materials may be estimated. One such relationship, from reference 90, is

$$da/dN = C\,(\Delta K)^n \tag{10}$$

where

da/dN = crack growth rate (inch per load cycle)

ΔK = difference between maximum and minimum stress intensity during cyclic loading ($K_{max} - K_{min}$)

C = a material constant

n = a material constant

Another frequently used equation, from reference 91, is

$$da/dN = C\,(\Delta K)^n/[(1 - R)K_c - \Delta K] \tag{11}$$

where

K_c = critical stress intensity

R = ratio of minimum to maximum stress intensity during cyclic loading

Either of these equations may be used to predict the growth of a crack from some initial dimension a_i during cycles of tank pressurization, if the material constants C and n have been properly evaluated. Evaluation of these constants requires a program of cyclic loading tests on precracked specimens that represent the tank as to material, material thickness, and fluid environment. Equation (10) differs from equation (11) by the requirement that these constants must also be evaluated for each distinct loading ratio R. Equation (11), on the other hand, attempts to provide for the effects of loading ratio.

A further consideration in the use of either of the above equations is the fact that crack growth characteristics frequently are observed to change as the crack progresses. When this condition occurs, the material constants must be evaluated for each distinct growth region. Cases in which three distinct growth regions were identified are treated in reference 92.

Another method for correlating data on cyclic crack growth, perhaps simpler than those discussed above, makes use of the ratio of the initial stress intensity (based on the initial crack depth and the maximum cyclic load) to the critical stress intensity for unstable crack propagation. The higher this ratio, the lower the number of cycles of loading to fracture. This approach has proven useful for correlating crack-growth data in the cyclic life region of less than 1000 cycles, when the critical crack depth is less than the material thickness. Details of this approach and its application to pressure vessels are covered in reference 4.

The various approaches that have been developed for correlating cyclic crack growth data under complex loading conditions tend to become inaccurate with increasing load variation and increasing complexity of loading spectra. Such limitations are evaluated, and representative spectral loading test data are obtained whenever it appears that the available methods for data correlation may not be sufficiently accurate.

Regardless of the method used to evaluate cyclic crack growth, it should be noted that when loading cycles occur in the presence of a fluid environment other than dry air, it usually is necessary to consider the possible effects of such environments on crack growth. Further information on cyclic crack growth, including considerable test data on materials of interest for tankage, is provided in reference 84.

2.2.4.2 SAFE-LIFE ANALYSIS

The fracture-mechanics treatment of unstable crack propagation, environmental effects, and cyclic crack growth can be combined to verify analytically the ability of a structural system to withstand service loading and exposure conditions in the presence of a starting crack of a given size (refs. 2, 3, and 4). In such calculations, the initial crack sometimes is arbitrarily assumed, but a more realistic starting point is to consider the capability of applied nondestructive inspection. In this approach, the largest crack that could escape detection is assumed as the worst-case starting crack. A third method for establishing the starting crack size is to compute it from the stress associated with proof pressurization and the material stress intensity for unstable crack growth (usually the K_{Ic} value). This approach involves the assumption that cracks just under the critical size for unstable propagation during proof testing actually exist in tanks that pass proof testing.

With the maximum possible initial crack size thus established, the crack growth during pressurization cycles can be determined as described previously. The reliability of a tank is verified when the final computed crack size, at the end of the cyclic life preceding final service pressurization, is smaller than the size that will grow in the service environment at the maximum operating pressure.

By reversing the above procedure, it is possible to begin with the largest crack that will not fail in service and work back to the crack size that should just pass proof testing without failure; from this crack size, together with the known material stress intensity for unstable crack growth, the required proof pressure can be computed. Further, to avoid failures during proof testing, the computed flaw size associated with proof testing becomes the standard by which flaws that must be eliminated during manufacturing and inspection are determined, since flaws larger than this size will cause fracture during proof testing. This procedure for determining the reliability of a pressure vessel or, alternately, for establishing proof–testing requirements that guarantee the safe life, termed the "proof-test logic", is covered comprehensively in references 3 and 4.

The ability of a safe-life analysis to prevent service failures may be jeopardized if subcritical cracks are capable of significant growth without failure during the proof-testing cycle. Current evidence indicates that there may be many materials, especially those at medium levels of strength and relatively high fracture toughness, that are capable of such growth without unstable propagation during a single cycle of loading. With such materials, loading to the proof stress can produce crack growth without fracture. After unloading and then loading a second time to a stress significantly below the proof stress, growth can again occur, this time possibly to a critical size, whereupon fracture occurs. Investigations of this phenomenon have demonstrated its existence in 2014-T6 aluminum, 2014 aluminum welds, Ti-6Al-4V STA, Ti-6Al-4V annealed, and D6Ac alloy steel heat treated to 205 ksi yield strength; the results of these studies are reported in references 93 and 94. With these materials, or any material suspected of behaving similarly, the conditions under which such subcritical crack growth occurs and the magnitude of the growth must be determined and accounted for in the performance of the safe-life analysis (ref. 3, sec. 5).

2.2.4.3 ADDITIONAL ELEMENTS IN A FRACTURE-CONTROL PROGRAM

Quality Control. – The toughness of production tank material is subject to considerable variation as a result of the effects of a large number of material and processing variables. Only by providing quality control of material toughness can one obtain production parts in which the toughness values meet or exceed those used in fracture-mechanics analyses. Quality is controlled by performing fracture-toughness tests on unwelded and welded material obtained from selected areas on production or preproduction parts. In addition, all material scheduled for the manufacture of tanks is subject to testing to ensure that toughness requirements are met after production processing.

The elimination of flaws large enough to affect tank performance, both in incoming material and in fabricated tankage, is an important factor in a fracture-control plan, because such elimination prevents or minimizes proof-testing failures and contributes to reliability in service. The most commonly used flaw-detection methods for tankage are dye-penetrant (for flaws that reach an accessible surface), radiography, ultrasonic inspection, and, for ferromagnetic materials, magnetic-particle inspection. A review of the capabilities of these flaw-detection techniques (as applied to solid rocket motor cases) is provided in reference 16 (pp. 9, 10, 41, and 42).

Qualification Testing. Hardware qualification programs, performed to verify the adequacy of design and of fabrication processes, are an important adjunct to a fracture-control program. Typically, tank qualification programs involve complete physical, chemical, and metallurgical evaluation of structural components, nondestructive and dimensional evaluation of structural test items, functional and structural testing of tanks, and fracture-mechanics-based analyses of tank fractures. Structural testing of tanks usually includes cyclic pressurization, sustained pressurization (often while the tank contains the fluid to be contained in service), and burst testing. The qualification testing performed to verify tanks for the Apollo Command and Service Modules is delineated in reference 95.

The performance of actual tankage when cracks or crack-like flaws of various sizes are present may be evaluated by performing a series of burst tests on preflawed tanks that are similar in material, geometry, and fabrication processes to the final hardware, but may be subscale in order to effect testing economics. Tests of this type provide an accurate reflection of tank fracture toughness by taking into account not only the manufacturing variables, but also the effects of biaxial loading, curvature, and material thicknesses (which frequently are less than the thickness required for development of plane-strain conditions).

Documentation. Maintenance of a system of documentation, sometimes referred to as the "tank pedigree", provides information necessary for predicting the structural capability of a given tank at any given time. Complete documentation enables a component or material to be traced back through all major test, fabrication, repair, and processing steps and associated inspection records to the original material acceptance test results. It also provides a continuing record of tank use that contains all pressurizations and conditions experienced during any operation, including peak pressures, environments, temperatures, and number of depressurization and repressurization cycles; and notes also any mishaps suffered and corrections made and any other events that may affect the tank structural performance.

2.3 TANK STRUCTURAL DESIGN

Vehicle tanks and the smaller internally mounted subsystem tanks have many design problems in common. They each have weld joints, access openings, support fittings, and accessory attachment provisions. Both may be required to withstand external collapsing pressures during preparation for propellant servicing or during decontamination. Vacuum frequently is used to evacuate gas from the liquid side of expulsion devices and to promote removal of residual propellants from tanks. To preclude accidental collapse of tank shells, the rigidity necessary to withstand one-atmosphere external pressure often is incorporated in the membrane design. The massive size and the compressive loading requirements usually imposed on vehicle tanks, however, introduce design considerations that are not particularly pertinent to subsystem tank design.

Minimum weight is always of prime importance in design but it is by no means the sole arbiter in optimum vehicle design. Many trade studies are made to evaluate weight relative to a variety of other factors such as cost, schedule, producibility, reliability, and availability of material, technical skills, tooling, and testing facilities. These factors are particularly significant because of the size of the final product. To minimize welding, for example, the largest possible sections of raw stock are used; this practice, in turn, dictates massive equipment and facilities for machining, handling, and welding.

In the structural-design phase, the complete detail design of the vehicle tank including sidewall, fore and aft bulkheads, access openings, and accessory mounting provisions is established on the basis of the tank material selected during the configuration-optimization phase. The major structural junctures (e.g., the skirt/bulkhead/sidewall juncture (fore and aft), and intertank bulkhead (if used)-to-tank sidewall juncture) are also established.

The design of smaller, monocoque subsystem tanks, although less complicated than the design of vehicle tanks, is a critical engineering activity. Failure of a subsystem tank under working stress usually propagates into catastrophic damage to adjacent structure and components. The continuing necessity for weight reduction in space vehicles has forced development of minimum-weight, low-margin tanks.

Design of a high-performance tank, where minimum weight is the overriding consideration, requires detailed structural analysis following the establishment of shape and size (volume) during configuration optimization. Unlike vehicle tankage, for which material is selected during the configuration determination phase, the material for the smaller subsystem tanks usually is selected in the design phase. Weld-joint design, tank membrane thickness, ports, access openings, tank membrane penetrations, internal accessory provisions, and tank support provisions also are established. Frequently, initial limited knowledge of tank usage requirements makes it neccessary to restrict the preliminary design to forging, tooling, and interface provisions. As information on tank usage becomes more definitive, the final design analysis is performed.

2.3.1 Safety Factor

The design of a tank usually is defined on the basis of the relation between the loading conditions that will be imposed on the tank and the capability of the tank to withstand these loads. Limit load, design safety factor, design load, allowable load, and margin of safety are tank design terms that are used to define the relation between tank loading and tank loading capacity. These terms are defined as follows:

Limit load (or pressure): Maximum expected load (or pressure) that will be experienced by the tank structure under the specified conditions of operation, with allowance for statistical variation.

Design safety factor: An appropriate arbitrary multiplier greater than 1 applied in design to account for design contingencies such as slight variations in material properties, fabrication quality, load magnitude, and load distributions within the tank structure.

Design load (or stress): Product of the limit load (or pressure) and the design safety factor.

Allowable load (or stress): Load (or stress) that, if exceeded, produces tank failure. Failure may be defined as buckling, yield, or ultimate, whichever condition prevents the tank from performing its function.

Margin of safety (MS): Fraction by which the allowable load (or stress) exceeds the design load (or stress):

$$MS = \frac{1}{R} - 1$$

where R is the ratio of the design load (or stress) to the allowable load (or stress).

In general, the magnitude of a safety factor is a reflection of the degree of confidence in materials properties, production processes, and the validity of the predicted usage conditions. Ideally, design safefy factors for each component in a liquid rocket would be established by determining analytically the values that would result in the desired probability of success in the intended application. This safety factor therefore would incorporate the effects of variations in material properties, fabrication quality, load redundancy, and precision of analytical techniques. The design safety factor should relate mathematically to the desired reliability with an associated confidence level. Theoretically, each component would have its own safety factor, which would be cost and weight optimized against all other components to achieve the desired overall vehicle structural reliability.

Unfortunately, the state of the art has not developed to the point where a rigorous mathematical approach is possible. Instead, a uniform design safety factor for the entire vehicle structure is established, and, largely on the basis of experience and judgment, a wide range of margins of safety greater than zero is used for the various components. Values for design safety factors in current use for vehicle tanks range from 1.0 to 1.1 for yield and from 1.25 to 1.5 for ultimate, the higher values being used for manned flight vehicles. In the smaller subsystem tanks, a wider range of safety factors has been used, probably because the tank weight does not increase significantly with somewhat larger margins of safety.

In the design of components such as positive expulsion devices or baffles that perform or withstand a cyclic type function, the safety factor usually is defined in terms of, and attained by designing for, expulsion or slosh cycle requirements that exceed mission-related cycles.

2.3.2 Loads Analysis

Vehicle-tank structure must be adequate not only to withstand the loads from vibration, thermal shock, propellant slosh, and tank internal pressure, but also to provide the main load path for vehicle body loads. Thus, it is necessary to consider all conditions of loading during the design phase, because the type of loads can influence the selection of tank construction: compressive loads may dictate semi-monocoque construction, whereas pure pressure loads may dictate membrane-type construction. Vehicle-tank subassemblies are subjected to different types of loading conditions and therefore must be examined separately.

2.3.2.1 TANK SIDEWALL

Vehicle-tank sidewalls are subjected to pressure, propellant inertial forces, axial load, and bending moments. Loads in the hoop direction are determined by combining the tank ullage head pressures and load pressure with the propellant inertia forces. The longitudinal loads result from a combination of ullage pressure, tank axial load, and bending moment. Methods for combining these loads are shown in reference 96.

2.3.2.2 END CLOSURE

Loads imposed on the end closures of vehicle tanks are the result of the tank ullage pressure and acceleration forces on the propellants. During boost, aft bulkheads have a maximum pressure at the apex, whereas forward bulkheads have minimum pressure at the apex. To establish the load at a specific location on the end closure, both pressure and closure geometry must be considered. Methods for determining these loads are described in reference 97.

2.3.2.3 INTERTANK BULKHEAD

Where there are separate and individual bulkheads on two adjoining tanks, the load on each is determined as described above for tank end closures. The single "common bulkhead", however, is subjected to either burst or collapse loads and to temperature gradients through its thickness. Applied loads (pressure) at any given point are calculated in the manner described for tank end closures, except that the bulkhead "feels" only the difference between the forward and aft pressures at any given point. To maintain stability under collapsing pressure loads, the bulkhead is designed to have a large bending stiffness (as compared with a membrane bulkhead). Consequently, the resulting design (stiffened skin or sandwich) requires a more sophisticated internal-loads analysis. This generally is accomplished by a multilayered shell-of-revolution program (refs. 98 and 99) that takes into account the extensional, shear, and bending stiffnesses in both the hoop and meridional directions of both facing sheets and core. A membrane bulkhead is satisfactory if caution is exercised in maintaining a positive Δp in the right direction.

2.3.2.4 ATTACHMENT

Loads are imposed on a tank at the points where other portions of the system are mated to the tank. The magnitude and direction of the loads generally are a function of the weight of the attached component or subsystem multiplied by the established amplication factor for acceleration and vibration forces. Only the attachment bolts and the most immediate structure feel these loads in full magnitude. To a great extent, experience and judgment are used to determine the magnitude of load on the adjoining structure by making due allowance for the damping that occurs as the force progresses from the point of excitation. Axial growth of vehicle tanks poses no restraint on tank function, but attachment of subsystem tanks must be analyzed carefully to allow for the loads generated at the attachment points by changing pressure and temperature.

2.3.3 Membrane Thickness

Except in rare cases, liquid rocket propulsion system tanks are thin-wall structures, i.e., the wall thickness is less than about one-tenth the tank radius (ref. 100, p. 293). This permits the use of simple stress formulas in the trade studies of simple geometrical shapes such as spheres and cylinders. Tentative material selections and corresponding membrane thicknesses and operational stress levels are obtained by using only mechanical-property data in conjunction with arbitrarily selected factors of safety. Practical considerations of producibility, handling, and stiffness are evaluated to validate these preliminary selections.

Before material is selected, working stress level, membrane thickness, and fracture-control consideration must be taken into account. The material must possess suitable levels of toughness and resistance to subcritical flaw growth to ensure compliance with intended tank service life. Material selection is followed by definition of the proof-test stress, operational stress, and NDI requirements consistent with mission performance requirements, as discussed in section 2.2.4.2. In the determination of membrane thickness, the most restrictive condition (e.g., safety factor, fracture-control criteria, producibility, or handling) must be identified and employed.

Because of its strength/density ratio, a certain material may provide a weight advantage analytically that is negated by further investigation. In trade studies made for the propulsion-system tanks for the Apollo Service Module, it was determined that fiberglass provided the lightest weight tank. However, the addition of reinforcements for reaction of the support loads, tank membrane penetrations, and attachment of closeout doors negated the weight advantage, and 6Al-4V titanium alloy ultimately was used. Sometimes the analytically permissible thinness of the tank membrane may be outside the limits of proven fabrication techniques, or it may result in extremely fragile tanks. For example, the shells for the positive expulsion tanks in the Apollo Service Module required a hemispherical membrane thickness (6Al-4V titanium) of 0.011 in. based on pressure considerations only, but manufacturing and handling considerations dictated the 0.023-in. thickness that presently is used.

In the case of vehicle tanks, for which material is selected during configuration optimization, the designer proceeds directly to establish membrane thickness. The membrane thickness for a vehicle-tank sidewall is dictated by the product of hoop tension load under the maximum anticipated internal pressure times the factor of safety. The sidewall membrane usually is stiffened against buckling by various means such as stringers, frames, or ribs spaced in a waffle pattern. In some cases (e.g., the Atlas and Centaur vehicles), additional membrane rigidity is attained through the internal working pressure within the tank.

2.3.4 Sidewall

Sidewall design is especially important in the design of large vehicle tanks, which generally not only contain the vehicle propellants but transmit vehicle body loads as discussed in section 2.3.2.1. The principal sidewall designs for pressurized vehicle tanks are skin-stringer-frame, waffle, and monocoque construction. Selection of the optimum type of structure is dependent on the magnitude of the externally applied body loads and the type of propellants to be contained. Highly loaded sidewalls generally are designed with skin-stringer-frame construction, whereas lightly loaded sidewalls are waffle construction. Very lightly loaded sidewalls can be monocoque construction but usually must be pressurized for stability.

2.3.4.1 SKIN-STRINGER-FRAME

Integral stiffening is the form of skin-stringer construction that is best suited for propellant tanks. This design eliminates the thousands of potential leaks associated with the mechanical attachments between the skin and the stringers and frames of conventional construction. Two configurations of skin-stringer design shown in figure 5 consist of (a) panels in which the skin, "blade" stringers, and horizontal ribs are machined as an integral unit, frames being attached mechanically to the horizontal ribs after the panels are formed; and (b) panels in which only skin and "T" stringers are machined, and frames are added after forming by

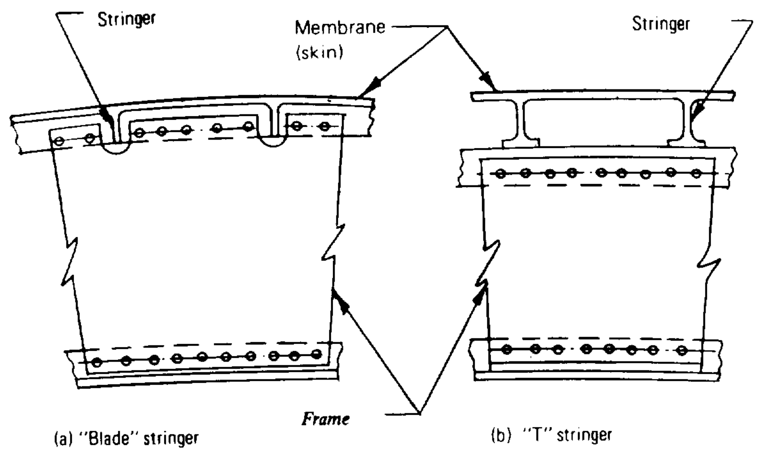


Figure 5. – Two kinds of skin-stringer-frame construction.

mechanical attachment to the inboard flanges of the T stringers. The blade design is lighter in the lower load regime, whereas the T-stringer design is lighter at higher load levels. Membrane thicknesses are based on the hoop tension loads under maximum expected internal tank pressure. Stringer spacing is dictated by local stability requirements. Stringer configuration and frame spacing for minimum-weight structure are based on general stability requirements under critical (varies with temperature) axial compression loads in combination with internal pressures. The material used must be readily machinable and have good forming and welding characteristics. Welded joints are highly desirable as a means to avoid propellant leakage. Since tensile design allowables for a weld are lower than those for the parent material, compensation is made by an appropriate increase in thickness at the weld joints. It is desirable to design so that the skin does not buckle at the design load. Skin buckling also impairs the reliability of any external insulation and causes sudden changes in the flexural stiffness of the vehicle stage. The stiffener spacing required to keep the skin unbuckled at limit load is determined from curved-panel buckling data, due account being given the stabilizing influence of tank internal working pressure. Once skin thickness and stringer spacing have been fixed, computer programs (ref. 101) can readily optimize the stringer and frame configuration to provide the load-carrying capability that meets the required column buckling and general stability requirements. Figure 6 shows a typical sidewall construction successfully used on the LH_2 tank for the Saturn S-II stage.

2.3.4.2 WAFFLE

A tank membrane stiffened by integral ribs that are arranged in a "waffle" pattern is a form of construction that not only is efficient in the usual loading range but also possesses many

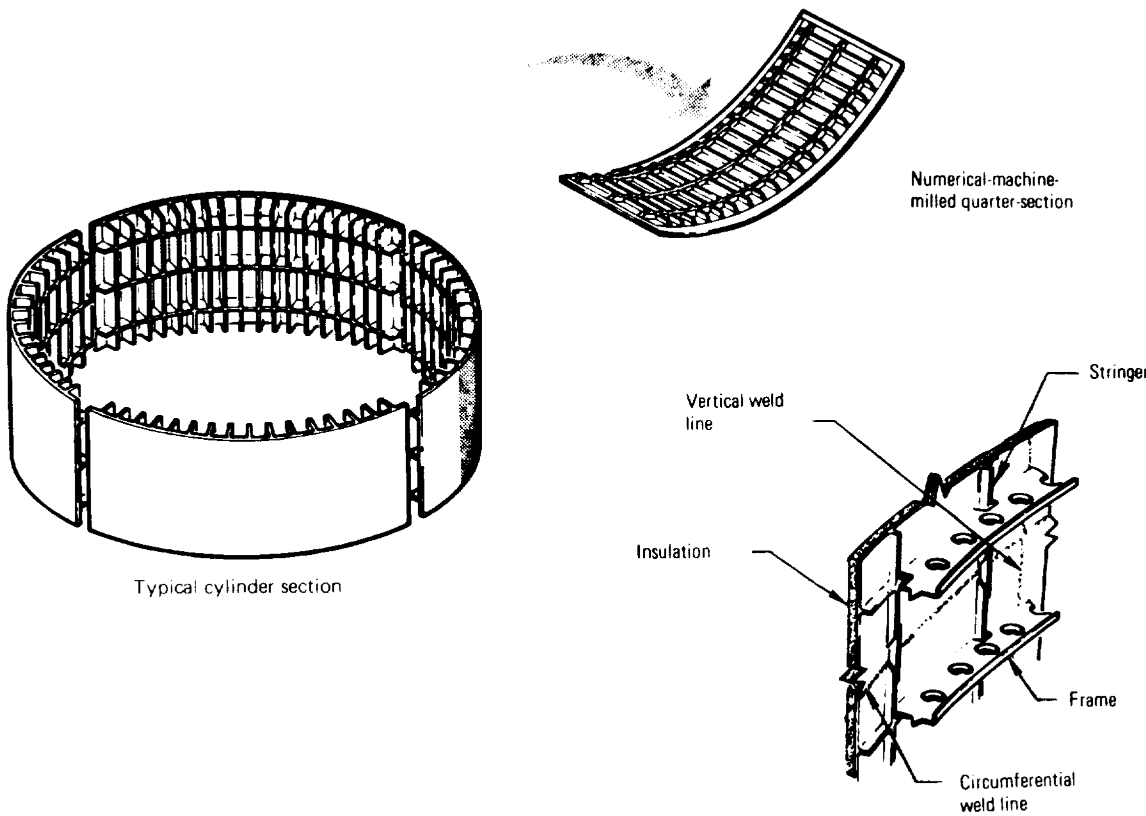


Figure 6. – Sidewall construction on LH_2 tank for Saturn S-II stage.

manufacturing advantages. Waffle construction is utilized in the design of the Saturn S-IV-B stage. The integral rib stiffeners usually are formed by mechanical or chemical milling of the waffle pattern in a thick plate; mechanical milling is the more efficient method. Design of the waffle structure usually is dictated by primary shell stability requirements; therefore, a low density material is advantageous. The plate material usually is easy to machine, and fabrication is economical. Because of these two considerations, aluminum-alloy plate is a prime candidate for the waffle plate material. Figure 7 shows two kinds of waffle configuration, square and isogrid.

In the widely-used square pattern (fig. 7(a)), the rib spacing is such that the individual skin panels will buckle under the same load that will cause a general instability or failure of the entire vehicle tank cylindrical structure. The general instability mode of failure is

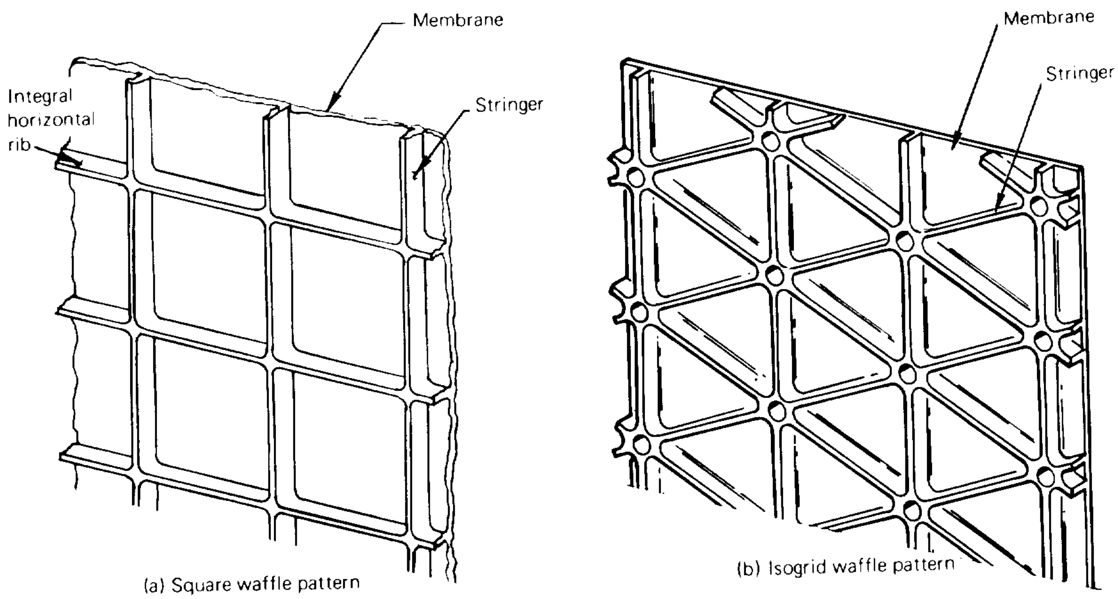


Figure 7. – Two basic waffle configurations.

determined as the critical buckling load of an equivalent isotropic cylinder. The waffle efficiency theoretically increases with increasing plate thickness and decreasing skin and rib thickness; however, minimum skin thickness is dictated by the hoop tension requirements. The rib spacing and height are optimized on the basis of this fixed skin thickness. Where the continuity of stiffening ribs is interrupted, weld lands are sufficiently thick to maintain shell stability. This construction constitutes a fabrication advantage in that all mechanical and individual rib splices are eliminated.

Another waffle design that has shown excellent promise is the isogrid configuration. Isogrid is a pattern of integral stiffening consisting of a gridwork of equilateral triangles, as shown in figure 7(b). This structural arrangement, currently used on the tankage on the Delta vehicle, has the following properties:

(1) The bending and extensional stiffnesses are independent of the grid orientation.

(2) No coupling between the grid and the skin due to Poisson-ratio effects exists for material with $\nu = 1/3$. This condition implies that strength calculations for inside or outside stiffening are identical.

(3) Because of properties (1) and (2), isogrid shell analysis is equivalent to that for monocoque when the proper equivalent thickness and equivalent modulus of elasticity are used. Because of the simplicity of the analysis, it is comparatively easy to optimize and design isogrid structure.

Analytical weight comparisons of rectangular waffle grid patterns and isogrid patterns have shown the isogrid pattern to be lighter. In addition, tests have shown that with isogrid construction, in comparison with rectangular patterns, appreciably higher stresses can be developed prior to buckling.

Waffle construction offers several other practical advantages: manufacturing is simple because of the elimination of internal structure; reinforced areas in the milling pattern for cutouts or attachment provisions are easily incorporated; and the fact that the skin will remain smooth and unbuckled precludes problems of debonding of, and damage to, external insulation.

2.3.4.3 MONOCOQUE

In general, pressure-stabilized monocoque construction results in the lowest structural weight. A material with a high tensile yield strength is necessary. Pressure-stabilized structures such as the Atlas and Centaur vehicles require extreme care during fabrication and transportation to preclude handling damage. Prevention of buckling in a pressure-stabilized monocoque structure requires that the meridional pressure stress be greater than the compressive meriodional stress created by external loads.

2.3.5 End Closure

End closures significantly affect cylindrical tankage length, and the basic end-closure configurations are established during the vehicle configuration optimization phase as described in section 2.1. Not only is the end-closure shape a consideration, but the closure between two tanks must be optimized; a selection must be made in favor of two separate bulkheads or one common bulkhead.

Theoretically, there are an infinite number of shapes from which to select. In actual practice, however, closure shapes usually represent a familiar geometric figure or minor variation thereof. For example, the Titan and Saturn S-IV tanks are designed with hemispherical end closures, Saturn S-II end closures are oblate spheroids, and the Atlas, Saturn IC, and Centaur tanks employ ellipsoidal end closures. Such standard geometric shapes facilitate weight analysis through computer subroutines as presented in reference 5. Figure 8 depicts some of the surfaces of revolution that have been analyzed by computer subroutines.

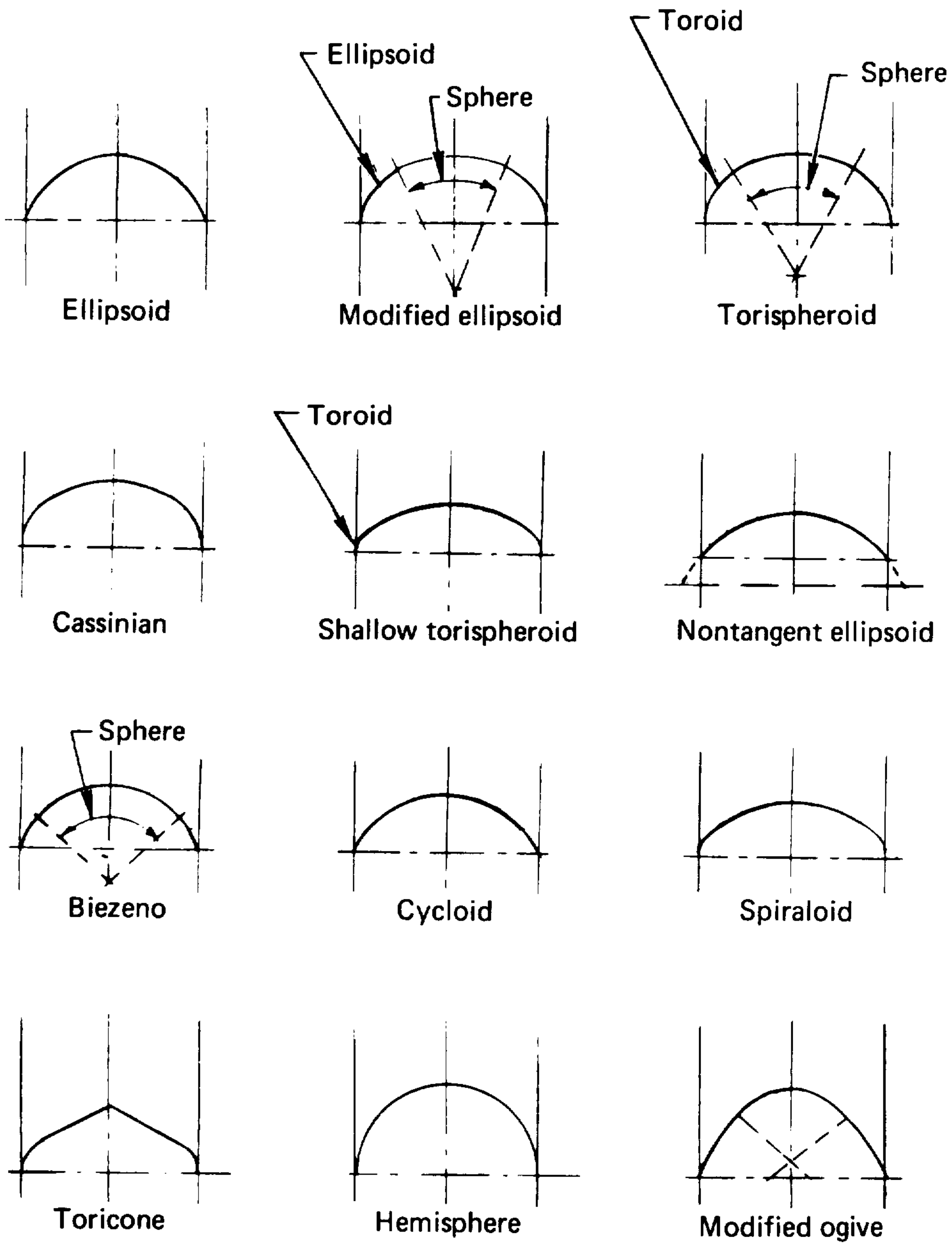


Figure 8. – Some surfaces of revolution that have been analyzed by computer subroutines.

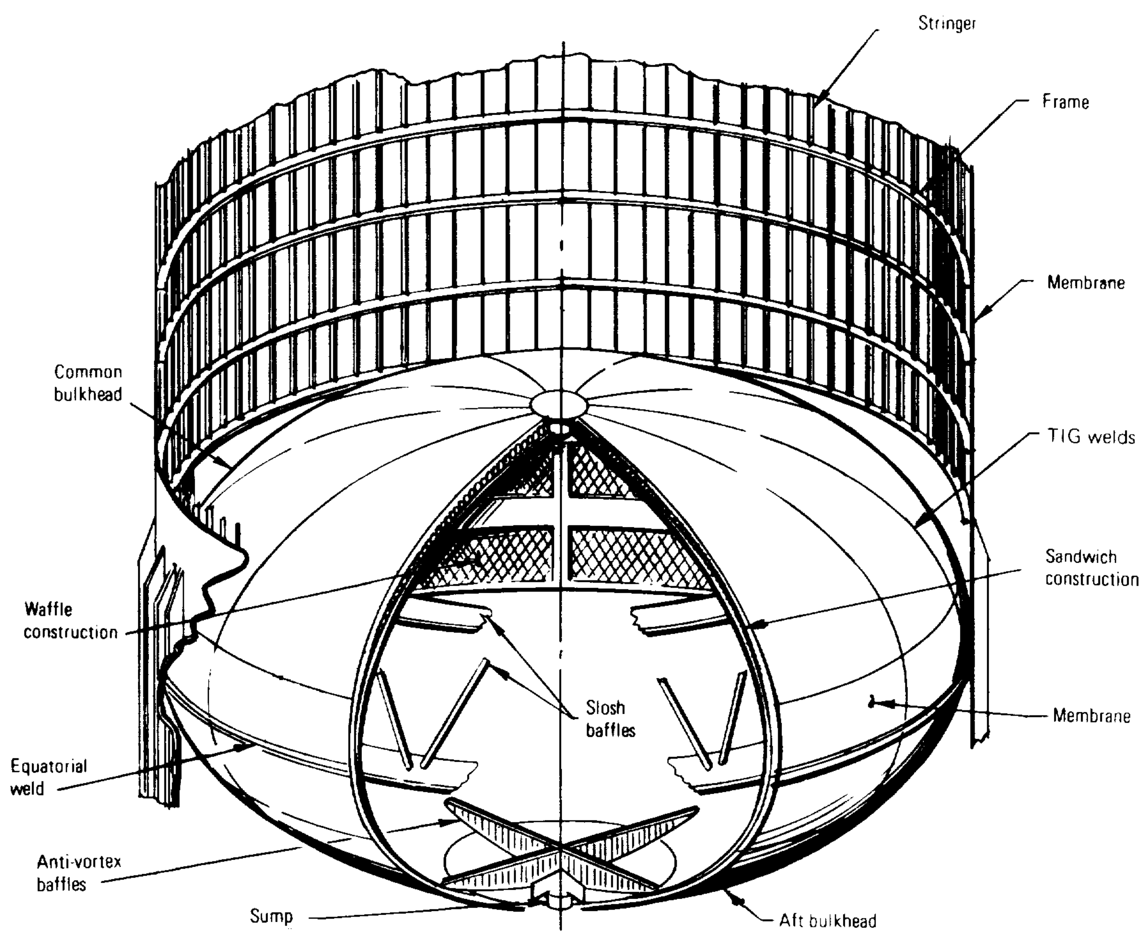


Figure 9. – Cutaway drawing of the LOX/LH_2 tanks in the Saturn S-II stage.

Figure 9 shows the end closures used in the LOX tank of the Saturn S-II stage. Sandwich construction is employed to resist buckling where compressive loads exist, whereas a simple membrane construction is adequate for the areas loaded only in tension.

An example of honeycomb sandwich structure is shown in figure 10. For given facing materials and thicknesses, the core depth and density are dictated by the requirement for preventing primary instability and "face wrinkling" of the facing sheets. The variation of unit weight of the composite sandwich structure with the ratio of thickness of the two facings is investigated, and the optimum arrangement is determined.

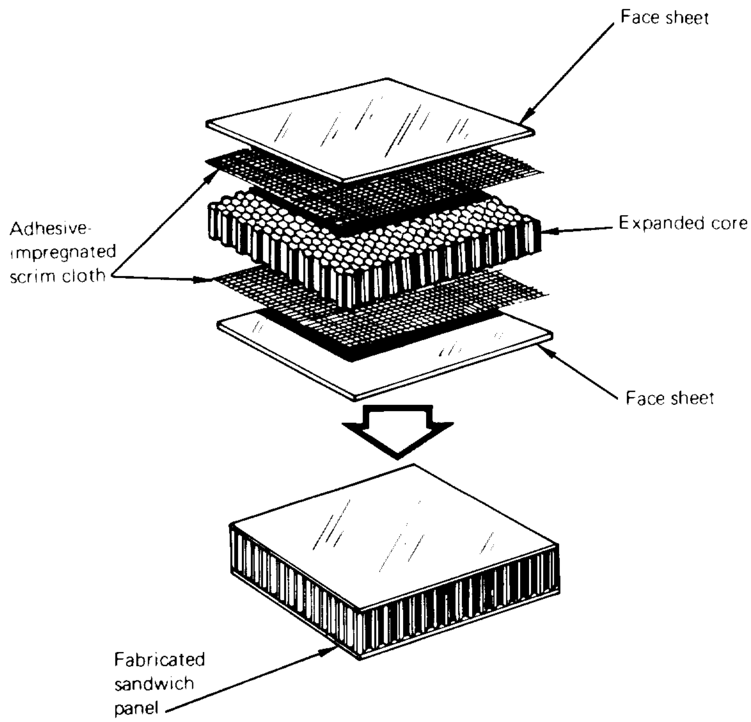


Figure 10. – Example of honeycomb sandwich structure.

The use of sandwich construction for the intertank bulkhead of booster tanks offers the possibility of significant weight savings. When tank internal pressures are low and shell instability is the critical problem, the facing sheets can be designed to operate at stresses close to the material compression yield stress. The total facing thickness is dependent on stresses associated with maximum tank pressure. The facings may be critical either under ultimate strength requirements in which the hoop tension stresses due to tank pressure are of primary importance or under yield requirements in which the combination of thermal and pressure stresses is of significance. Reference 102 presents typical methods used in selecting honeycomb sandwich structure.

2.3.5.1 FORWARD BULKHEAD

This bulkhead generally is convex (external surface), loaded primarily by bursting pressure; a thin sheet or "membrane" is the usual design approach. In a thin-shell design, the head-depth-to-diameter relation must be analyzed to determine compressive stresses in the knuckle radii to ensure that no circumferential buckling pattern occurs. These analyses generally must be confirmed by tests, since information on buckling of heads due to internal pressure is meager.

To achieve minimum weight, the shell thickness is tapered so that the entire bulkhead is operating at the maximum allowable stress level in the meridional direction, regardless of shape. For minimum cost, however, a constant-thickness bulkhead is more desirable. Although a single-piece bulkhead is preferred, material size and current forming methods such as spin-forming, stretch-forming, hydroforming, or explosive-forming make this impossible. Generally, therefore, the bulkhead is designed to be fabricated by welding together a single central "dollar" section to a welded subassembly consisting of a number of gore segments. This practice avoids the juncture of the multiple welds where the gore sections meet at a common point. Hoop compressive stresses usually are avoided, the result being certain restrictions on bulkhead local radii of curvature, which in turn results in height-to-radius limitations.

Figure 11 shows a typical weight optimization curve for the Saturn S-II stage generated by the subroutine of reference 5. The curves show graphically the weight variations of tank sidewall, skirt, and bulkhead as the configuration of the bulkhead is varied. For the loading condition of the Saturn S-II LH_2 tank, the hemispherical bulkhead results in the heaviest structure, because of the necessity for a long skirt length.

2.3.5.2 AFT BULKHEAD

Aft bulkheads differ from forward bulkheads only in that hoop compressive forces may develop under certain conditions of loading. The region from the equator to the liquid level always will be in hoop compression during filling (assuming no ullage pressure), and compressive stresses also may occur during flight as a function of bulkhead local curvatures and the ratio of ullage pressure to acceleration-induced forces.

Aft bulkheads generally require waffle or sandwich construction or other kind of circumferentially stiffened structure in the upper portion. Minimum-weight design generally will dictate a shell of revolution with changing curvature and varying geometry. There are no reliable techniques for the stability analysis for this type of structure under the varying biaxial load conditions encountered. It is, therefore, mandatory that the analysis be conservative and that it be complemented with stringent verification testing. An additional significant consideration is that aft bulkheads must provide for engine feedlines. A central location is the preferable choice for a single engine.

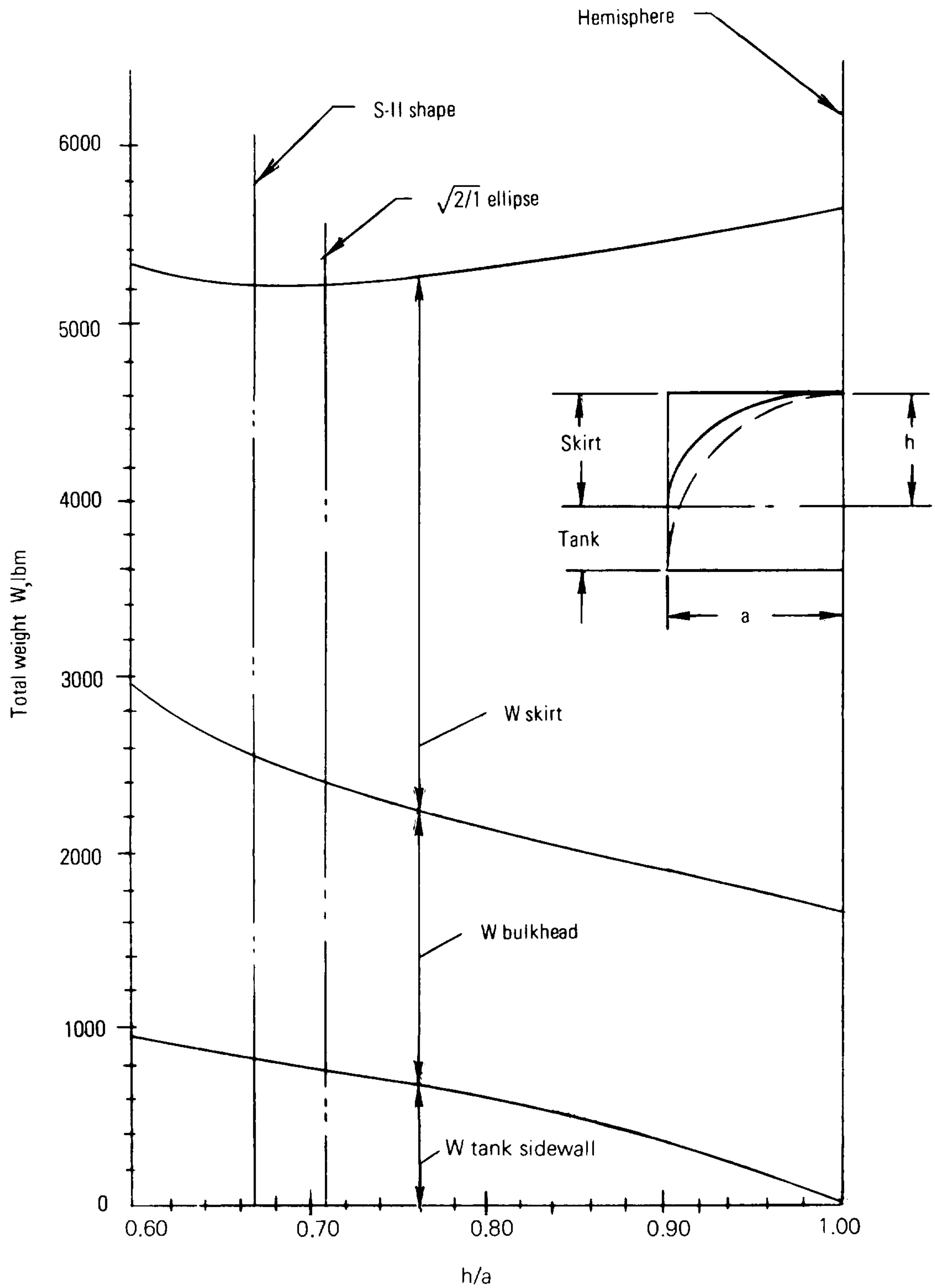


Figure 11. – Variation of tank weight with variation of end-closure configuration (LH_2 tanks for S-II stage).

2.3.5.3 INTERTANK BULKHEAD

The fluids in a bipropellant vehicle are separated physically (and possibly thermally) either by two separate membrane bulkheads or by a common bulkhead. Figure 12 shows the two bulkhead concepts.

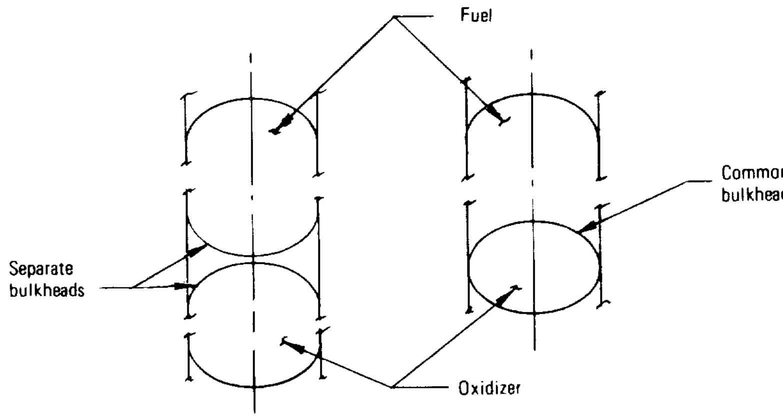


Figure 12. – Sketches of two basic types of intertank bulkheads.

The common bulkhead may be either self-supporting or pressure-stabilized. One feature of dual separate membranes is that space for and access to the fluid lines coming from the bottom of the forward tank is provided. Consideration must be given to the special problems involved in routing these lines either through or around the forward bulkhead of the lower tank.

There are several unique features in the self-supporting type of common bulkhead that make a determination of bulkhead weight versus bulkhead height somewhat more complex. The bulkhead must be designed for both bursting and collapsing pressures. The bulkhead therefore is of waffle or sandwich construction to provide stability under collapsing pressure. If insulation also is a requirement, sandwich construction usually is the most efficient, but consideration then must be given to both thermal and pressure stresses. Convex-vs-concave bulkhead (forward surface) attitudes are evaluated in connection with the relative magnitude of the burst-vs-collapse pressures. In general, consideration of the routing of the forward-tank propellant lines makes the convex (forward surface) attitude more desirable. Trapped residuals in the forward tank are minimized by the use of low-density filler material in the volume below the propellant outlets.

2.3.6 Attachment Junctures

2.3.6.1 WELD JOINTS

Weld-joint design is one of the most critical requirements of sound vehicle tankage structure. Since weld strength is less than that of the parent material, adequate load capacity must be achieved by increasing material thickness at the weld joint. Ideally, the thicker weld land would be made symmetrical about the membrane material. However, the expense of milling both sides and the desirability of maintaining a smooth exterior surface for aerodynamic reasons are overriding considerations that lead to the eccentric weld land configuration usually employed on booster tanks. Effective weld-joint strength can in some cases be improved by shaving the bead; this practice reduces stress raisers, removes the area most apt to contain flaws, and improves weld-joint ductility.

Optimum joint configuration can be achieved only by an extensive test program for determining the proper dimensions for the weld-land geometry for each material. Figure 13

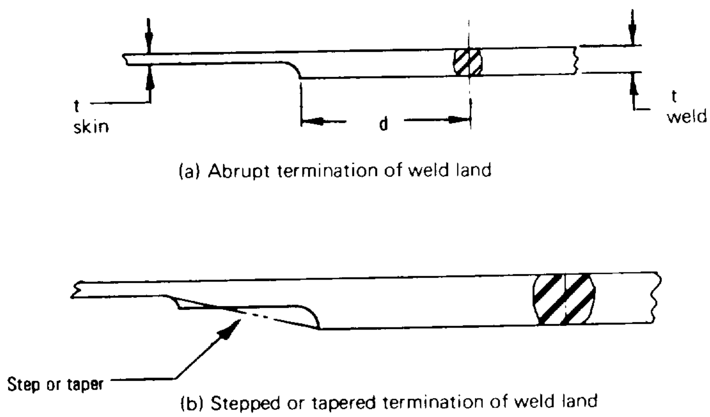


Figure 13. – Weld-joint configurations for vehicle tanks.

displays two weld-land designs for 2014-T6 and 2219-T87, two aluminum alloys commonly used in current vehicle tankage. Weld-land thicknesses range from 2 to 2¼ times the basic membrane thickness, and weld-land widths range from 1.25 to 2.00 in. The 1.25-in. width is the minimum required to prevent the heat-affected zone HAZ and the resultant strength reduction therein from reaching the fully stressed basic membrane. Weld-land thicknesses in excess of 2¼ to 2½ times the basic membrane thickness with abrupt terminations (fig. 13(a)) introduce bending stresses and some reduction in joint strength at the point where the basic membrane meets the weld land. This concentrated strength reduction is avoided by introducing a stepped or tapered section between the skin and weld land as shown in figure 13(b).

In the typical subsystem tank, the weld joint for assembling tank sections is potentially the predominant structural discontinuity. The designer's task is to minimize the structural discontinuity across this joint. Underdesign results in premature tank failure in the weld joint. Overdesign results in a ring or span of material that is much more rigid than the tank membrane; the resultant difference in deflection while the tank is under load causes flexure in the tank membrane and possibly lower cyclic life. Figure 14 depicts some commonly used preweld joint preparations that have proven highly satisfactory in tank development programs to date.

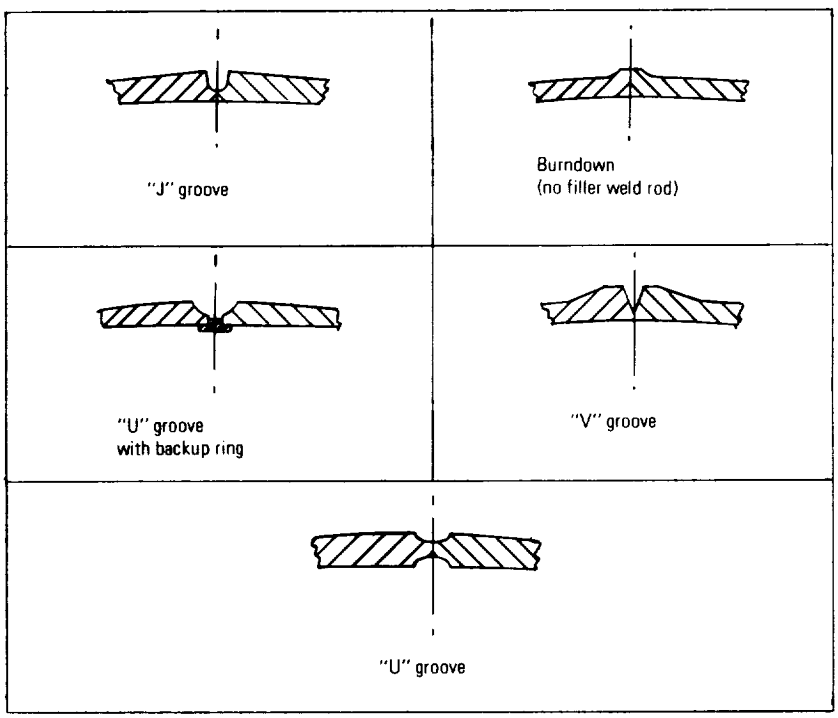


Figure 14. – Weld-joint configurations for subsystem tanks.

Since weld joints inherently are subject to variations in production, the experienced designer strives to minimize the linear length of weld joints in his tank designs. When possible, tank cylindrical sections are made by spin forging, thus eliminating longitudinal welds.

The probable introduction of distortion and oxidation, plus the need for elaborate equipment, preclude heat treatment of subsystem tank assemblies following welding. Postweld processing usually is limited to tank aging to relieve internal stresses caused by welding. The designer, as in vehicle-tank design, therefore increases the material thickness in the HAZ to compensate for the reduction in material strength that occurs as a result of annealing at and adjacent to the weld. Ideally, the gradations in loss of material strength would be precisely balanced by increased material thickness through a precisely contoured joint transition. From the practical standpoint, however, the additional joint efficiency and weight reduction frequently do not justify the attendant analysis and machine contouring effort, and a straight-taper joint transition is used.

Use of sophisticated chemicals and high-performance components in liquid rocket systems has emphasized the necessity for fluid cleanliness and for tanks that are cleanable. It may be noted in figure 14 that, except for the joint with a backup ring, the joints will be readily cleanable. In tanks with small ports, where interior access subsequent to welding is limited, it is mandatory that the weld-joint design require negligible cleanup following weld.

2.3.6.2 BULKHEAD/SIDEWALL JUNCTURE

A critical item in the design of liquid rocket tanks is the method of joining the major structural components (e.g., bulkhead to tank sidewall and skirt to tank sidewall). These junctures normally occur at a common location and almost always are accomplished with an appropriate fitting. A widely used fitting is a "Y" ring, so named because of its cross-sectional appearance. Examples of Y-rings, as used on the Saturn IC and the Titan II, are shown in figure 15. A different method, used on the Centaur, provides an angle for mechanical attachment of the skirt (fig. 16).

The Y-ring type of joint serves the following functions:

- Provides a structural load path from bulkhead to tank and from skirt to tank.
- Provides a leak-proof container.
- Provides easy inspectability and weld repair prior to skirt installation.
- Provides for mechanical attachment of skirt.
- When properly designed, creates low hoop stresses in the difficult meridian welds (three in Saturn IC tank) that splice the Y-ring segments.

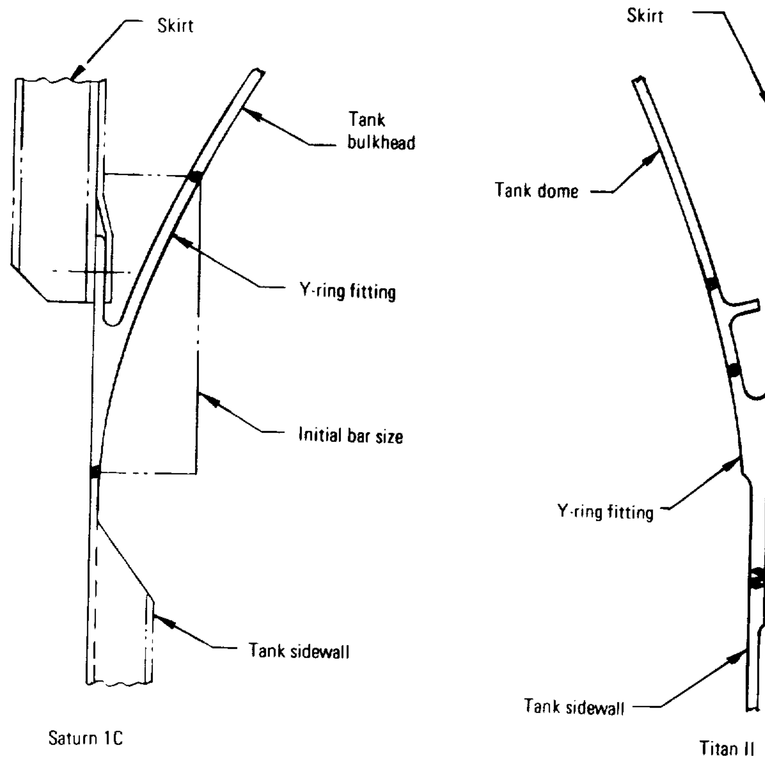


Figure 15. – Examples of Y-ring bulkhead/sidewall junctures.

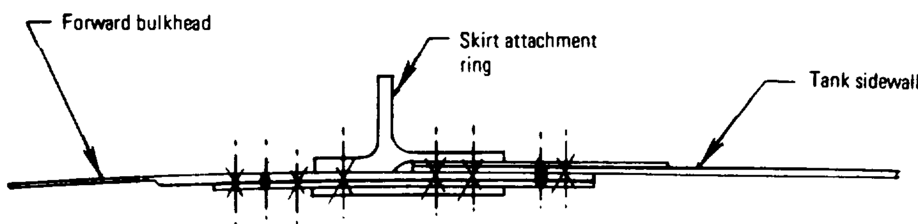


Figure 16. – Example of bulkhead/sidewall juncture used in Centaur.

A principal disadvantage associated with this type of joint is the difficulty associated with making the ring-splice meridian welds. This welding usually is accomplished in one of two ways:

(1) The initial bar stock is rolled to tank contour, the weld joint is prepared, and the entire cross section of the bar is welded by an extremely large number of passes. The desired cross section then is machined from the completed bar ring.

(2) The bar stock is machined to the desired cross section and formed to the required contour. The circumferential splices then are made by one or two welding passes along each leg and stem of the "Y".

The completed Y-ring then is mated to the bulkhead and tank sidewall by a circumferential weld and is mechanically spliced to the skirt.

The splice-joint buildup used on the Centaur tanks employs simple flat sheets for stiffening the membrane in the area of the skirt attachment ring.The ring (T-section) is machined from a circular forging, thereby eliminating welding of ring segments.

This method has the following advantages:

(1) It avoids expensive forgings, machining, and associated tooling.

(2) The bolting ring works with a variety of configurations, and mating of adjacent structure is comparatively simple.

(3) Weld discrepancies are easily repaired.

It has the following disadvantages:

(1) The method requires spot welding through as many as five layers of skin.

(2) The thin sheets require stringent control of weld schedules.

(3) Vehicle separation requires a circumferential shaped charge to fracture the ring.

2.3.6.3 BOSSES AND SUPPORT PROVISIONS

Attachment of system components and tank mounting structure generally is accomplished by providing local support points or bosses in tank structure. To avoid tank penetration, the bosses are made deep enough to accommodate mechanical fasteners. When the basic structure is made from a stock size of sufficient thickness, these bosses are integrally milled with the basic structure. This process creates "hard spots" that remain flat during forming and force the adjoining structure to do additional straining during both forming and subsequent tank tension loading. Additional local reinforcing is provided to minimize this excess straining by distributing the strain over a larger area. The reduced eccentricity and increased distance from the basic thickness to the hard-spot thickness minimize bending stresses at the discontinuity.

When system attachments are made to thin-shell structure such as a membrane bulkhead, the use of integral bosses requires a much larger initial material thickness and more extensive milling. Fabrication of attach bosses also can be accomplished by welding a circular machined ring (containing the boss) to the bulkhead; however, residual stresses from the welding can cause severe warpage in thin, compound-curvature bulkheads (less severe for flat or hemispherical shapes). This warpage can be minimized by the use of hard tooling and close tolerance parts and by shrink-fitting fitup procedures before welding. However, scrappage rate is high because of the limited repairability of this type of weld.

The nonintegral support provisions involve welding machined fittings (ports, flanges, support pads) to the tank membrane. This practice requires either providing a ring of thicker material in the tank membrane to compensate for the strength loss from welding or lowering the permissible tank operating pressure. In addition to structural analysis of the designs, the designer must consider both accessibility for tank cleaning following welding and distortion of the tank membrane due to weld heat. An advantage of nonintegral fittings is that the tank designer has more latitude in the method of fabrication of the tank membranes.

Although the integral fittings complicate membrane forging and machining, experience has shown that they are superior to welded fittings because of the absence of heat distortion, strength reduction, weld-induced contamination, and uncertainty about weld integrity that attend welded joints. To minimize the effect of integral-fitting discontinuities on the tankshell, however, the tank designer strives to minimize the number of fittings. Frequently, in gas-pressurant tanks, the fluid ports and tank supports are combined into a common boss. In liquid propellant tanks, the single access opening is attained by use of a closeout cover that contains both the inlet and outlet lines. When multiple tanks are used in series, the inlets usually are connected to standpipes within the tanks to preclude reverse migration of the fluids and to ensure series feedout.

Internal standpipes and stillwells in liquid-carrying tanks usually require end supports to withstand liquid slosh impact and to alter vibrational response. These internal supports most commonly utilize a slip joint to allow for longitudinal expansion and contraction of the tank but provide support to the standpipe and stillwells against side loads.

2.3.7 Openings and Access Doors

For purposes of this monograph, the term "openings" applies to all types of ports and access openings in the tank membrane. Openings and access doors are treated together because they represent similar design problems in membrane discontinuity. Ideally, the tank membrane would have no openings or access doors; realistically, of course, these provisions are required. Tank openings and access doors for propellant tankage generally are located at or near the apex of the bulkheads. This location has the advantage of being relatively easy to fabricate and simple to analyze, and it facilitates entry into the tank interior. The primary design objective is to prevent leakage throughout the entire life cycle. Two methods that employ integral bolting rings are illustrated in figures 17(a) and (b); the method employed on the Centaur for the forward door is shown in figure 17(c).

A bearing lip and oversize holes (fig. 17(a)) will reduce joint rotation due to eccentric bolt shear loading, whereas a large cross-sectional area in the bulkhead boss (fig 17(b)) will accomplish the same purpose by forcing most of the load to remain in the bolting ring and

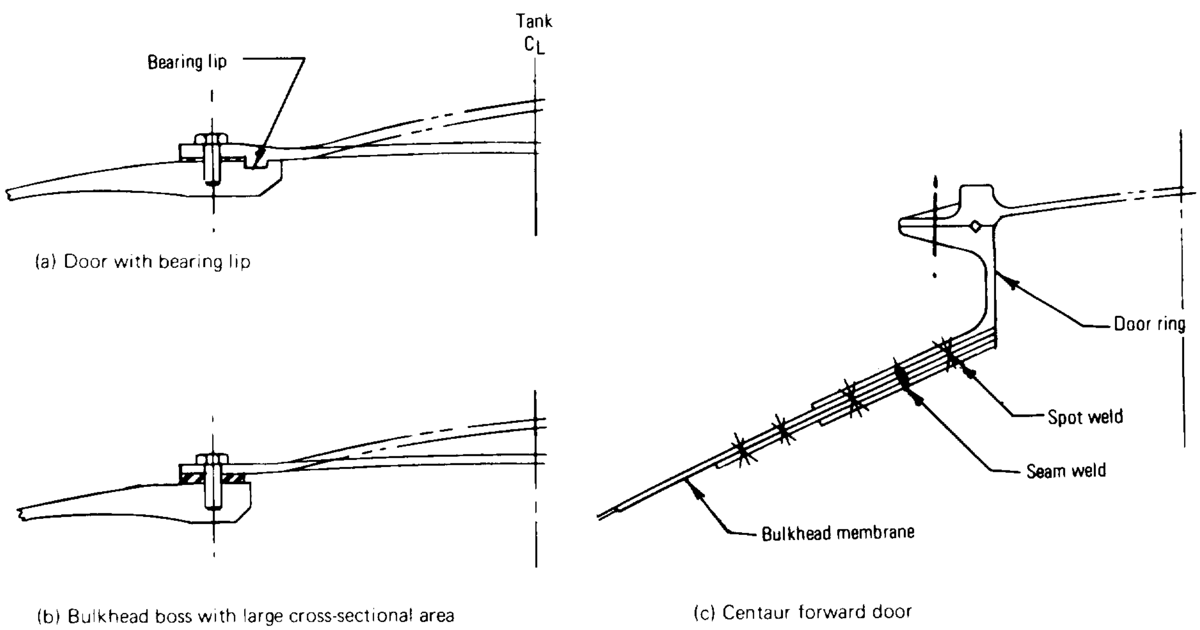


Figure 17. – Three designs for a tank access door.

not go through the door. Either design can incorporate a door of smaller radius of curvature than that of the adjoining structure in order to further reduce loads in the door, boss, and across the joint (dashed-line configuration).

Experience has also shown that in the design for a radial sealing gasket the final gap requirements between the door flange and the ring flange must be considered, since a local bending moment is induced as the torque is applied to the assembly bolts. It is desirable to select bolt spacing and seal and flange designs that minimize the final bending moment of the bolt joint.

Tank openings for system installations create local discontinuities at the attach points. The subject is discussed in section 2.3.6.3.

2.4 TANK COMPONENTS

2.4.1 Propellant Slosh and Vortex Suppression Devices

Sloshing of propellants can adversely affect vehicle stability and the integrity of the tank structure. Baffles are therefore provided to damp liquid motion. In cylindrical tanks, baffles generally take the form of flat rings attached to the structural shell as shown in figure 1; here they serve the double purpose of providing fluid damping as well as shell stability. For oblate spheroidal tanks, baffles may take the form of a truncated cone either perforated or open trussed. These cones generally are supported at the equatorial region and provide for liquid motion inhibition at the surface level only or throughout its height. A clear understanding of slosh and methods of counteracting it in large tanks may be obtained from the material in reference 103.

Fluid vortexing occurs at engine feed-line outlets; it is most severe at outlets in tank aft bulkheads, especially at central locations. Antivortex baffles generally take the shape of radial vanes either attached directly to the bulkhead skins or cantilevered outward from a central attachment. Figure 1 shows a method used for multiple outlets and figure 9 depicts a method employed for a centrally located fluid outlet.

2.4.2 Propellant Positioning Devices

A major problem in designing for a space environment is to provide a supply of gas-free propellant to the engine at the start of each firing cycle. In the near-zero-"g" operational environment of orbital spacecraft, gravitational forces are negligible, and capillary forces determine the propellant location within the tank. This capillary action, normally away from the discharge port, may be augmented by significant periods of adverse accelerations that may result from aerodynamic drag, midcourse corrections, or orbit-adjust maneuvers. If the propulsion system is to function properly, these forces must be countered by an expulsion system that will retain propellants at the tank discharge port.

Surface-force fluid-positioning devices have demonstrated the capability to function satisfactorily when a combination of these adverse displacement forces does not exceed the resisting capillary force of the device. Two basic types of surface-tension systems have been developed to satisfy various spacecraft propellant expulsion requirements. As shown in figure 18, these basic designs involve partial fluid control or total fluid control.

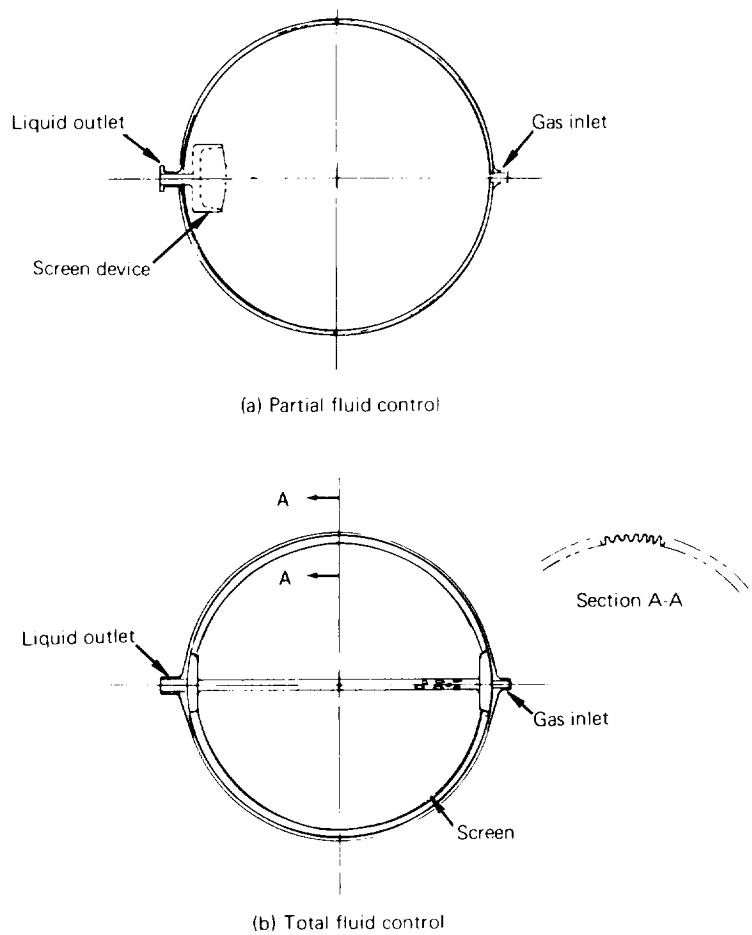


Figure 18. – Schematics of two basic types of surface-tension devices for fluid control.

Partial-fluid-control systems retain a sufficient quantity of propellant at the tank outlet to supply the engine during restart and to sustain flow until bulk propellant settling occurs. Partial-control systems generally are limited to unidirectional thrust applications, since they rely on engine thrust to provide propellant settling at the discharge port.

Total-fluid-control systems provide for communication from the tank discharge port to the bulk propellant throughout the operational life of the spacecraft. Examples of both partial and total control systems are discussed in detail in reference 104.

The design of a capillary or surface-tension device is rather complex, because it must consider not only the magnitude and direction of adverse accelerations but the physical properties of the propellant such as density, viscosity, and surface tension, each as a function of operating temperatures. In addition, vibration environments during operation (sine and random) affect the fluid capillary stability at the critical frequency of the surface-tension device, thereby reducing its capability; reference 105 discusses design practices for vibration environments. Cleanliness and surface condition of a surface-tension device also greatly influence its performance. Although relatively complex in design and analysis, surface-tension fluid-positioning devices provide passive simplicity in operation as well as reusability.

2.4.3 Propellant Expulsion Devices

In liquid rocket system applications where "g" forces imposed on tank fluids are either nonexistent or random in direction and magnitude, it is necessary to maintain the fluid continuously at the exit port of the tank. This is usually done by either containing or controlling the fluid with an expulsion device within the tank. Positive expulsion devices are those that provide a solid material interface barrier separating the pressurizing gas from the propellant. Actuated by pneumatic pressure, these devices either expand or contract to expel propellant from the tank on demand and, ideally, at constant flow rate and pressure. In addition, the positive expulsion device must control the bulk propellant to prevent liquid vortexing or gas ingestion. As tanks increase in size, the production of expulsion devices becomes increasingly difficult. Although a metal-diaphragm type of expulsion device has been designed and developed for a tank approximately 34 in. in inside diameter and over 55 in. long, it is adviseable to use fluid-positioning devices rather than an expulsion device whenever possible in the larger tanks. Through currently available production capabilities in welding and forming thin-gage bellows material, in obtaining uniform dispersion of Teflon sprayed on forming mandrels, and in precision molding of elastomeric bladders, positive expulsion devices are feasible for almost any application. Table III contains a listing of tanks that employ various types of expulsion devices. Figure 19 presents schematics of three basic types of expulsion devices.

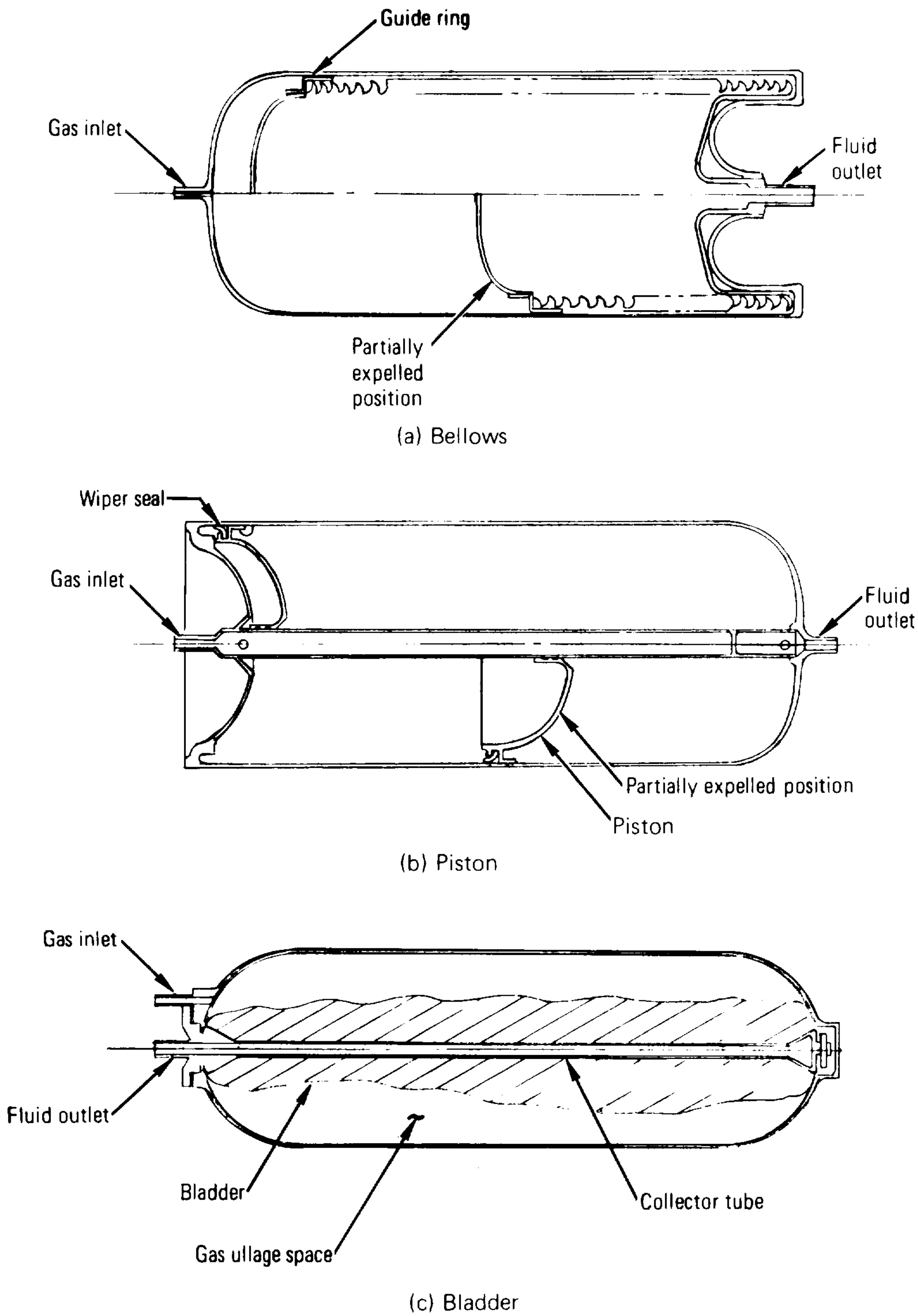


Figure 19. – Schematics of three kinds of positive expulsion devices.

Selection of the correct expulsion device approach for a particular application entails consideration of many factors. There are advantages and disadvantages to the various bellows, diaphragm, and bladder-type expulsion devices. The comparative importance of these advantages and disadvantages, however, frequently are subjective with the tank designers involved. The significant design considerations of the more commonly used designs (bladder and bellows) of expulsion devices are discussed in detail in the following sections.

2.4.3.1 EXPULSION EFFICIENCY

Expulsion efficiency for a fluid expulsion device is its ability, expressed quantitatively, to expel the liquid from the tank. One hundred percent efficiency simply means there will be no residual fluid in the tank after the expulsion device has completed its actuation, i.e.,

$$\text{expulsion efficiency} = \frac{\text{expelled volume}}{\text{loaded volume}} \, .$$

Associated with expulsion efficiency as a measure of the desirability of a given design for an expulsion device is the concept of volumetric efficiency, which is the ratio of loaded volume to internal tank volume, i.e., volumetric efficiency $= \dfrac{\text{loaded volume}}{\text{internal tank volume}}$.

Obviously, the total efficiency of a device is the product of the two, i.e., total efficiency = $\dfrac{\text{expelled volume}}{\text{internal tank volume}}$.

A characteristic of an expulsion device that must be considered in establishing expulsion efficiency is its resistance to actuation. A device that requires negligible pressure for its expulsion actuation is desirable because of its negligible effect on system pressure losses. If a device has an increasing resistance as actuation progresses, the designer must ensure that the system flow requirements are compatible with the resultant pressure loss.

Propellant that remains in the convolutions of a bellows expulsion device is an example of residual nonexpellable propellant. Bellows with a conventional cross-sectional configuration have a large radius between the bellows elements; this feature is not desirable, since it results in a larger quantity of residual propellant. The expulsion of propellant on the outside of the bellows by extension of the bellows is not desirable, because there is more space between the convolutions in the extended position than in the compressed position. Another cause of residual propellant in a bellows is mismatch of the shape of the moving head of the bellows with the end of the tank against which it nests. Expulsion bellows have been designed to maximize expulsion efficiency by using a bellows convolution that nests flat against the adjacent convolution and a moving head that matches the shape of the tank end. It is of interest that in all but one program the fluid to be expelled has been contained inside the bellows.

The piston type of expulsion device, although extremely simple in concept and theoretically capable of accomplishing 100-percent fluid expulsion, manifests various significant design problems. The cylinder wall must be sufficiently rigid to maintain acceptable dimensional relationships under working conditions. The piston seal requires a suitably smooth sealing surface and, if the seal is pressure actuated, excessive frictional drag against the tank wall must be avoided. The seal itself must be resistant to wear, chemical attack, and damage by particulate contamination, so that there is minimum possibility of fluid loss through the seal as piston actuation progresses.

Nonmetallic bladder devices that fold and crumple (usually randomly) as expulsion proceeds also trap fluids within the material folds. In addition, the perforated center standpipe, about which the device collapses, also adds to residual unavailable fluid. An expanding-bladder device requires provisions such as ribs either in the tank membrane or in the bladder itself to ensure that no liquid is locked in by the bladder. The rib requirement in turn contributes to fluid residuals and lower efficiency.

The diaphragm-type devices that nest in the tank shell present the best potential for extremely high efficiencies although expulsion efficiencies of 98 percent or better are not uncommon with both metallic bellows and nonmetallic bladder expulsion devices. In volumetric efficiency (ratio of expellable volume to tank-envelope volume), however, there is a significant difference. The flexible-material devices able to assume the shape of the tank are obviously superior in this respect. Furthermore, the convolute height in the bellows devices contributes to an increase in tank envelope (volume) without a corresponding increase in expellable volume.

2.4.3.2 MATERIAL

The choice of material for an expulsion device is closely interrelated with usage environments and device configuration. In addition to the obvious requirement that the material be fabricated to the design configuration, two significant material characteristics are permeability and compatibility.

Common materials used in the metallic bellows and diaphragm designs are 300-series stainless steels, high-nickel alloys, and 1100 and 3003 aluminum. These materials can operate satisfactorily over a wide range of temperature, provide a positive sealing barrier between propellants and pressurant systems, and are compatible with most liquid rocket chemicals. Metal-foil diaphragms are frequently used in applications where only one fill-and-expulsion cycle is required. When repetitive cycles are required, the more substantial bellows or reversible-diaphragm construction is required.

In the case of nonmetallic bladders, materials have been primarily butyl rubber and Teflon, Teflon being predominant because it is inert to almost all liquid rocket chemicals. Plastics such as Mylar, Kapton, Dacron cloth, Nomex paper, and other polyester films have been investigated for use at cryogenic temperatures. Obviously, the choice of a bladder material for use at cryogenic temperatures is based primarily on its flexibility at that temperature. Most materials become rigid and crack or tear when flexed at temperatures of liquid oxygen or liquid hydrogen. The choice of a material thickness is also important, since thinner films are more flexible than thicker films. However, if the film used is too thin, it will not have enough strength to resist the bladder stresses or it will be ineffective against permeation of liquid or gas.

Permeation.– Diffusion of pressurization gas and propellant through the membrane of an expulsion device such as a bladder is of concern because of the possible detrimental effect of gas bubbles on engine performance and of propellant vapors on upstream system components. In a bladder or diaphragm assembly, pressurization gas and propellant counterpermeate an organic barrier material until the equilibrium point is reached. Equilibrium occurs when the vapor pressure of the propellant is reached in the gas ullage space (fig. 19(c)); then the propellant partial pressures across the membrane are balanced. Should the propellant become saturated with the gas pressurant prior to attainment of the propellant vapor-pressure balance, the pressurant gas will continue to permeate. The resulting gas bubbles in the propellant compartment of the expulsion device later will be detrimental to engine performance.

Gas bubbles can be prevented by use of a nonpermeable material such as metal for the expulsion device or by use of a thin metallic barrier within a laminated nonmetallic material such as Teflon. When these approaches are not feasible, it is possible to employ measures at the system level to prevent gas bubbles. One technique is to control the imbalance in propellant and gas permeation rates by providing ullage volume appropriate for the differential permeation rate; another is to seed the gas ullage space with propellant to accelerate the vapor-pressure balance (ref. 106).

Compatibility. – Compatibility considerations involve not merely material being degraded by various liquid rocket chemicals but also the possible catalytic decomposition of the liquids by the expulsion-device material. The latter is undesirable because gas bubbles form in the propellant and the pressure rises in the propellant tank.

Hydrazine decomposition occurred in the tanks of the Ranger and Mariner/Mars midcourse-correction propulsion systems. A pressure rise of 1.5 psi per day was noted when the test temperature was 125° F, but this rise diminished to zero when the test temperature was reduced to 90° F. A tank pressure rise also occurred during flight missions (ref. 107). It was found subsequently that the butyl rubber compound and the fillers used in the bladders (e.g., carbon black) in the tanks were the major cause of the problem. A new compound, ethylene-propylene terpolymer Number 10, was developed; it causes a very low rate of hydrazine decomposition.

Compatibility considerations must also include chemical solvents used in cleaning and flushing or in testing processes. Referee propellants used for acceptance testing may effect physical property changes in organic materials (refs. 108 and 109) that in the test environment can result in permanent damage to the expulsion device. Teflon materials have been intensively investigated because of their wide acceptance as the preferred material for expulsion bladders. This preference results from its chemical inertness and stability when in contact with the chemically active liquid rocket fuels. A standard construction for Teflon bladders has been a thin-film laminate of an inner layer (fluid side) of TFE 30 and an outer layer of FEP 120, both Teflon materials. This construction was used on the bladders for the Mariner/Mars 1971 mission. Failure of these bladders during flight-acceptance tests, in which various solvents were used as referee fluids, led to an investigation to determine the cause. This investigation identified the sensitivity of the standard Teflon laminate to solvents such as Freon-TF and isopropyl alcohol and the tendency to incur solvent-stress cracking at strains below six percent when biaxially stressed. The tests also demonstrated that the standard laminate is susceptible to stress cracking by N_2O_4 and MMH.

A new Teflon material, designated "codispersion laminate", was tested concurrently and was found to be insensitive to solvent stress cracking. This material replaced the standard laminate material used in construction of the Teflon bladders. The codispersion laminate consists of 80 percent TFE 30 and 20 percent FEP 9511. Bladder construction consists of an inner layer of FEP 9511 sandwiched between inner and outer layer of the codispersion laminate. The investigation and results are reported in reference 110.

2.4.3.3 DESIGN MARGIN

The capability of the expulsion device to perform in excess of known requirements under usage environments and conditions is called "design margin". For example, cycle life beyond requirements and ability to withstand full working pressure and dynamic environments in excess of mission requirements are indications of design margin.

Cycle life. – Most expulsion bladders and diaphragms fold in an uncontrolled random manner that results in three-corner folds and creases in the bladder material. This behavior has been satisfactory for elastomeric bladders operating at room temperature but not for cryogenic-propellant bladders or metal bladders and diaphragms. Mylar and polyester/Nomex bladders with collapse-control devices completed 25 expulsion cycles without failure when tested in liquid hydrogen. The same type of bladders in tanks without collapse-control devices (random folding) failed after ten cycles.

Metal bladders and diaphragms without some type of rolling or folding control usually have not had reproducible operational characteristics. In rolling diaphragms, an adhesive between the diaphragm and the tank shell is used to control the "roll and peel" action of the diaphragm. Convoluting the diaphragm and telescoping it into one end of the tank also has been a satisfactory method of diaphragm control.

The most severe folding of a bladder occurs within spherical tanks, because of the amount of material that must eventually collapse ("wad-up") around the perforated center feedout tube. Insertion of the bladders into the tank shells is also a critical operation because of the possibility of damage to the bladders. The installation hole is usually of minimum diameter; hence, the bladder must be folded for insertion into the tank.

Orientation of tanks in the associated propellant system is also a significant factor. Cylindrical tanks with the outlet tube on the major axis and oriented horizontally require collapse of the bladder and evacuation of gas preparatory to filling. This operation is critical, since occasionally the collapsed bladder material lying along the lower tank surface will become entrapped by the weight of fluid being introduced. As tank filling continues, the bladder must successfully pull out the entrapped folds, stretch, or break. During the qualification test programs on the tanks for the reaction control system on the Apollo Command Module, it was also noted that the bladders in horizontally positioned cylindrical tanks usually incurred a twisting action. This twisting apparently was due to the tendency of bladder material to fall predominantly on one side of the central diffuser tube as the bladder collapsed. Subsequent fill-and-expulsion cycles can increase the total angle of twist until adverse bladder damage occurs.

The foregoing undesirable aspects can be avoided by providing flow-through capability within the expulsion bladder and by installing the tank with its major axis in a vertical position. The flow-through provision permits expanding (positioning) the bladder in the tank shell prior to introducing the fluids. It was determined on the Apollo program, however, that if the major axis of the tank were too long the expanding bladder would contact the tank wall during prefill positioning and hang up because of friction before it was completely nested in the upper hemisphere of the cylindrical tank. This behavior means that when tank filling ensues, folds of bladder could get trapped by the liquid, thereby stretching the bladder and resulting in possible adverse damage as tank capacity is reached. This condition occurred on a N_2O_4 tank on the Apollo Lunar Excursion Module. The problem was solved by undersizing the cylindrical section of the bladder by 1.5 to 2 percent.

A TFE/FEP laminate qualified early in bladder programs has been used for most of the Teflon bladders. However, tests indicate that the FEP layer fails at 1/10 the number of cycles required for the entire film to fail (ref. 111). Evidence of the failure of the FEP layer prior to the TFP layer has also been seen on failed bladders. The new codispersion-Teflon construction previously described has properties superior to those of the TFE/FEP laminate. Data based on machine crease tests (ref. 112) indicate that the codispersion has about 100 times the flex life of the laminate.

Since current space vehicle applications require only one expulsion under mission conditions, the requirement for multicycle capability as a measure of design margin is questionable. This is particularly true for expulsion devices that degrade with each full expulsion. Therefore, the designer should establish cycle requirements based upon the expected ground servicing and testing conditions.

Differential pressure capability. – Since expulsion devices effect a positive barrier between the fluid and pressurant sections of a system, it follows that full working pressure will be imposed across the device as liquid depletion occurs. High differential pressure is damaging to most expulsion devices. Teflon bladders such as those used in the Apollo spacecraft tanks fold randomly as expulsion progresses, striate severely and, occasionally, pinhole when a sustained differential pressure of 185 psi (working pressure) is applied. This problem was resolved by limiting the differential to 40 psi during system checkout activities. In general, resilient materials such as rubber are more resistant to this type of damage.

The allowable differential pressure across a metal bellows in its extended position is limited, since an excessive pressure may cause the convolutions to buckle. Partial buckling of the convolutions may markedly reduce bellows cycle life, and complete buckling of the convolutions may prevent the bellows from recycling (ref. 113). Although the bellows can take a very high differential pressure in the nested position without failure, complete compression under high pressure may reduce its cycle life. Therefore, a mechanical stop usually is incorporated to prevent complete nesting.

Dynamic environment capability. – Vibration, acceleration, and propellant slosh during launch of a vehicle usually are the most severe that occur during the mission. Vibration frequencies range from 30 to 2000 Hz; acceleration is seldom below 5g and may exceed 10g (ref. 107), with shocks of moderate level (<100g) and duration. At this point in a mission, the subsystem positive expulsion tanks are fully loaded except for required ullage. The added mass results in beneficial damping of the vibrational excitation induced in the tanks, and slosh is minimized by the full-tank condition. It has been determined, however, through testing with transparent tanks, that flexible bladders incur substantial flexing at the liquid-ullage interface during vibrational excitation of filled tanks; it is desirable therefore to provide resistance to flexure damage.

Resonant frequencies for most positive expulsion devices occur at low to moderate frequencies (<100 Hz) in the vehicle bending modes. Bladders and diaphragms of organic materials are particularly susceptible to damage in the low-frequency lateral slosh modes (ref. 114). This characteristic becomes increasingly significant in large tanks with moderate to large ullage volumes (ref. 115). Metallic units can experience impact and abrasive damage in this frequency range (ref. 116).

The metal-bellows assemblies for propellant tanks on the Minuteman III vehicle were subjected to extensive vibration and shock tests. The initial 6-mil stainless-steel bellows assembly provided insufficient spring rate to resist buckling loads imposed by the 30-g, 18-millisecond terminal-peak sawtooth shock test. Also, the design pitch/span ratio was excessive, the result being an operating pitch too close to the critical buckling pitch. The design changes to solve this failure mechanism included an increase in metal thickness to 7 mils, an increase in the number of convolutions to decrease the operating pitch, and the incorporation of a guide pin that limited the rotational moment of the movable head.

Acceleration is of minor concern with flexible-bladder expulsion devices, since they do not as a rule have to resist the fluid motion. Lateral acceleration of a tank with a bellows device, however, can produce unsymmetrical fluid pressures on the movable head of the bellows. This condition can cause the head to tilt at an angle to the axis of the bellows and thus cause some bellows convolutions to be overextended and to buckle. This problem in the Minuteman post-boost control-system tanks was resolved by welding a guide pin to the center of the movable head that fits into a recess in the end of the tank. The pin, along with a circumferential guide ring (fig. 19(a)) around the bellows head, prevented the head from cocking to any extent that would cause overextension of the convolutions.

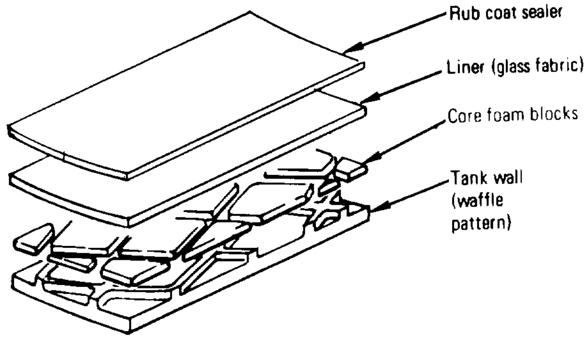
2.4.4 Tank Insulation

The insulation design for structures used for cyrogenic fluids is of considerable importance because of the effect of cryogenic temperatures on material properties. Insulation is applied either internally, as on the Saturn S-IV-B stage, or externally, as on the Saturn S-II stage. Internal insulation is used when it is desired to retain room-temperature material properties for the tank structure and thus avoid the loss of material ductility and toughness that may occur at very low temperatures. External insulation permits the tank structural design to use the increased tensile strength of the material that exists at cryogenic temperatures.

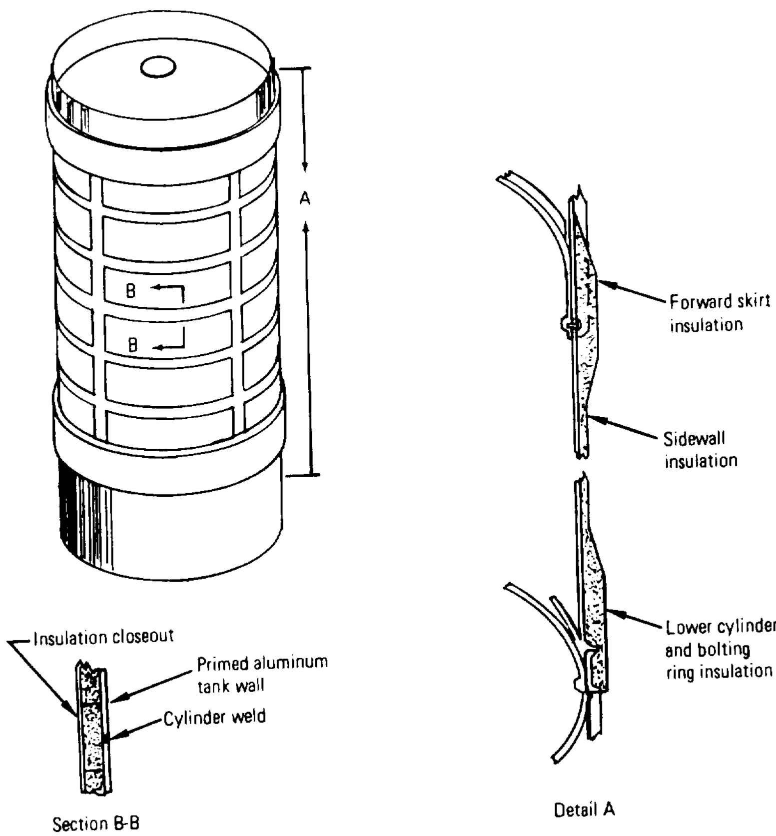
Three methods are generally employed for attaching the insulation to the tank walls: bonding, bolting, or spray foaming. The bonded and spray-foam insulations require careful surface preparation prior to installation, whereas the bolted insulation requires integral bosses in the tank structure; design of these bosses is discussed in section 2.3.6.3. Examples of the installation of internal insulation, bonded; external, spray-foam insulation; and external, mechanically attached insulation are shown in figures 20 and 21. An example of insulation of the Centaur intertank bulkhead is shown in figure 22. Moisture condensation, formation of ice, and loss of insulation performance or possible insulation damage require that extreme care be taken to ensure that external insulation is resistant to moisture or protected from moisture.

2.5 TANK DESIGN ANALYSIS

Design analysis, the key to a successful tank design, is the analytical prediction of the behavior of a vehicle or subsystem tank when subjected to both structural and dynamic loadings. This design analysis is performed concurrently with the detail design of tanks. The general procedure in tank design is to lay out the basic structural concepts and size the structure from the design analysis.



(a) Internal bonded insulation (S-IV-B)



(b) External spray-foam insulation (S-II)

Figure 20. – Examples of internal and external insulation.

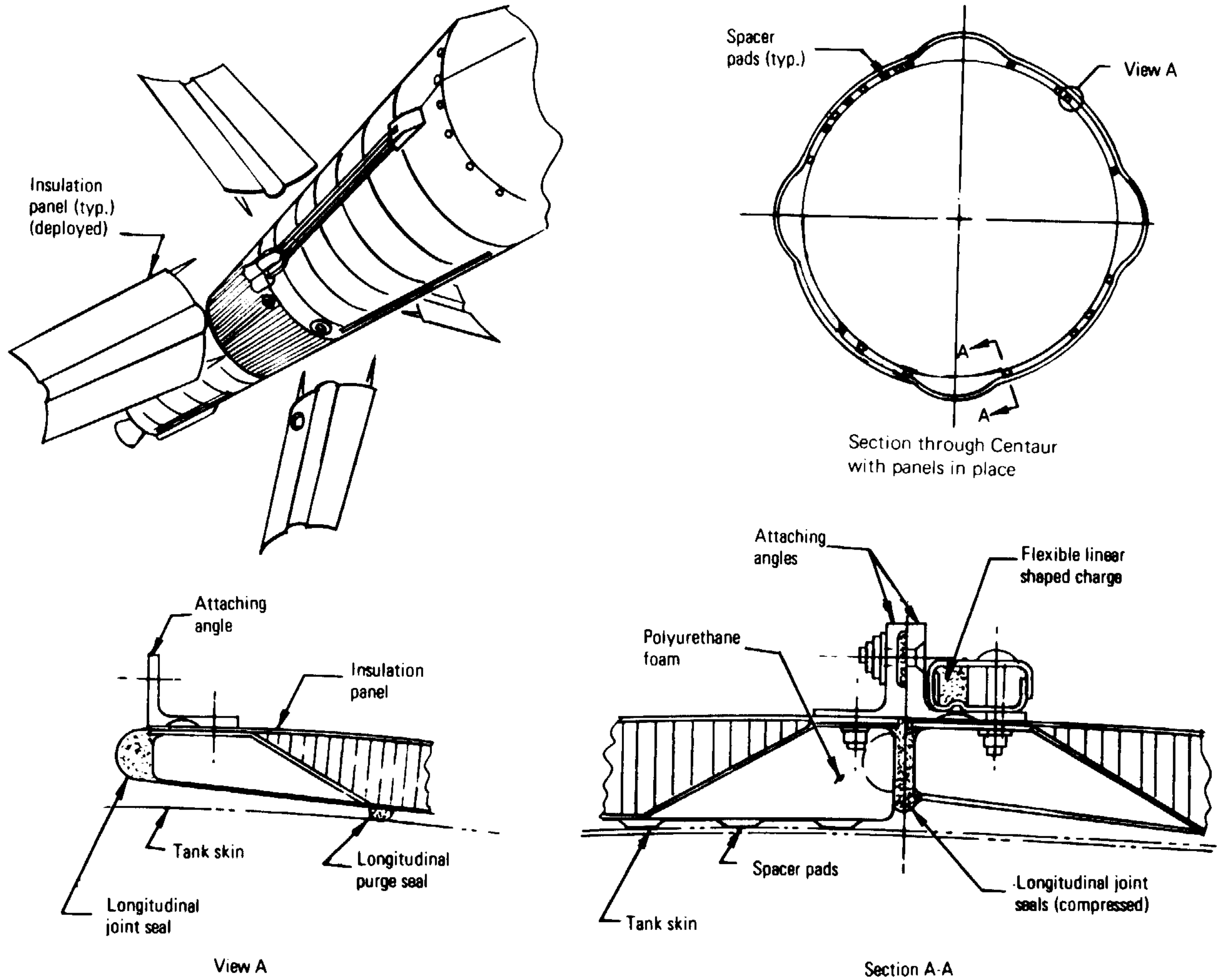


Figure 21. – Jettisonable insulation panels (Centaur).

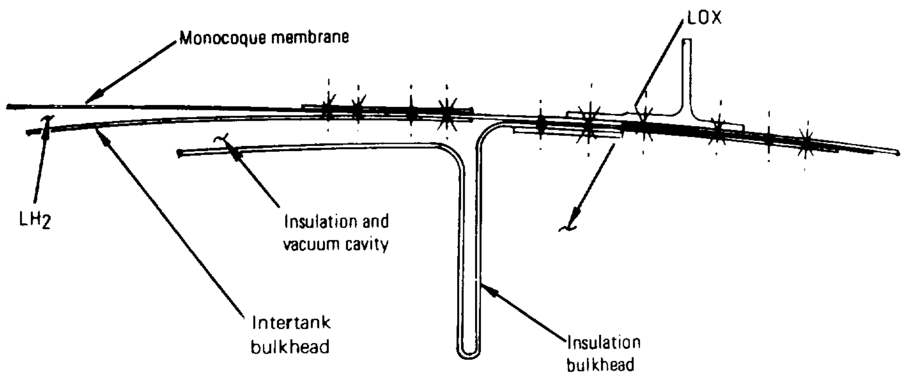


Figure 22. – Insulation of intertank bulkhead (Centaur).

2.5.1 Strength Analysis

Large vehicle tanks constitute sophisticated structures that are subjected to a multitude of loads (both magnitude and direction) during use. The smaller subsystem tanks of monocoque design are subjected primarily to internal pressure and concentrated loads at the support points; structural analysis for these tanks usually is not as extensive as that for vehicle tanks.

When the vehicle structure is analyzed to demonstrate adequate load capability, all elements of the structure undergo analysis by cost-effective techniques suitable to each particular application. Empirical methods developed for analysis of structural assemblies are used whenever possible, and theoretical methods, supported by special tests, are used when necessary.

In the usual analysis of shell structure for vehicle and subsystem tanks, elastic behavior for both limit and ultimate loads is assumed. The analysis is accomplished with the aid of computer programs for repetitive or complex mathematical procedures. The use of programs developed to take into account the effects of plasticity in a biaxial stress field is extremely difficult and rarely is warranted. The uncertainties of material properties in the plastic zone make the results dubious at best. A simplified linear-elastic theory produces results that are conservative and not significantly different from those obtained by much more sophisticated techniques.

2.5.1.1 TENSION-LOADED STRUCTURE

The parent material of the basic shell structure is analyzed for tensile yield or failure according to the basic stress and strain equations as given in any text on strength of materials (e.g., ref. 117). Tensile rupture may result from pure tensile loading or from the effects of combined bending and axial load. Margins of safety are determined by computing stress ratios and interaction curves as defined in reference 8. Allowable bending stresses are based on the "modulus of rupture" as determined by test and are a function of the material and the shape of the cross section (ref. 118).

It is difficult to perform an accurate stress analysis of eccentric welded joints that combine a known axial stress with an indeterminate bending stress. The weld nugget yields early, has no clearly defined proportional limit, and the major portion of the stress-strain curve lies in the plastic range. For the typical eccentric butt-welded joint shown in figure 23, high local yielding takes place at location A in the parent material and at location B in the weld, thus realigning the load through the weld nugget.

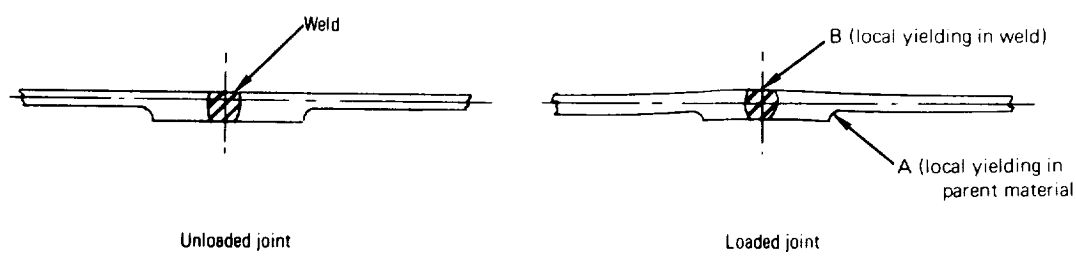


Figure 23. – Realignment of an eccentric weld joint under load.

Consistently reliable results have been obtained for large vehicles by basing allowable welded-joint strength on test coupons of representative configurations. Normal manufacturing imperfections such as porosity, mismatch, and oxides are included in the test specimens so that the statistically reduced allowables are realistic. These allowables are further reduced by 10 to 20 percent to account for biaxial and curvature effects and possible unknown scaling effects. The presence and growth of flaws during life cycle loading, their evaluation, and their relation to proof-pressure loading are discussed in section 2.2.4.

2.5.1.2 COMPRESSION-LOADED STRUCTURE

The skin-stringer-frame type of construction (sec. 2.3.4.1) requires analysis of the skin panels for local buckling and a determination of effective skin to be used with the stringers as columns between frames (ref. 119). A conservative column-end fixity coefficient of 1.0 can be used, or larger values can be established by test for any given configuration (ref. 96). The inboard caps of stringers are checked for local crippling under a combination of maximum shell axial compressive load and maximum internal pressure. The Poisson effect of the internal pressure causes compression in the stringers, and the restricted radial deflection at the frames causes stringer bending. This bending adds maximum compression to the inboard stringer cap midway between frames. Analytical procedures are given in reference 120. General stability is accounted for by sizing and spacing the frames according to methods provided in reference 6.

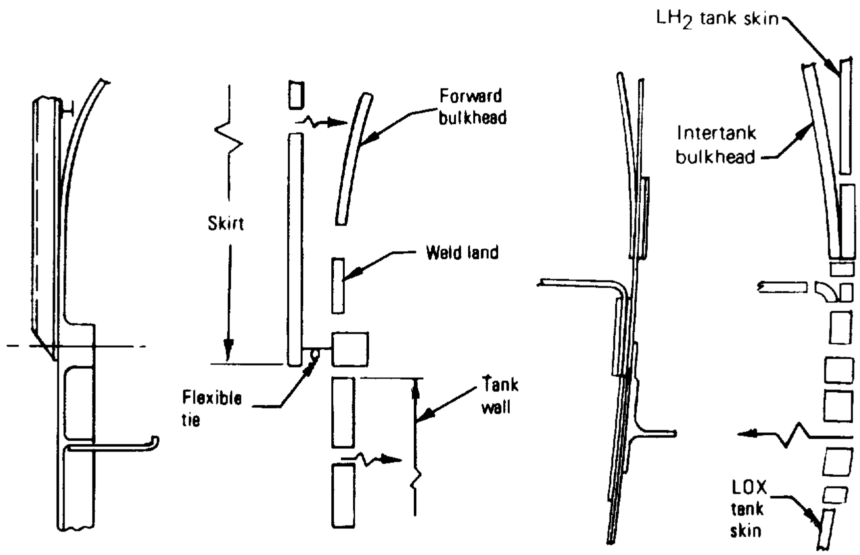
The waffle type of shell construction (sec. 2.3.4.2) subjected to compressive loads and internal pressure is analyzed for the general stability mode of failure in the same manner as an equivalent monocoque cylinder. The skin panels are checked for local buckling, and the ribs are checked for crippling. Methods of analysis are given in reference 121.

To prevent buckling in a pressure-stabilized monocoque structure (sec. 2.3.4.3) the meridional pressure stress must be greater than the meridional stress created by external loads. In the case of the Atlas vehicle, incipient buckling is allowed to occur at limit load. Thus, at ultimate load, the tank skin is in the buckled condition for a portion of the circumference. This postbuckling strength is available only when most of the imposed load is a bending load. Methods for analysis of postbuckling are given in reference 122.

2.5.1.3 MAJOR JUNCTURES

Major junctures are analyzed by computer programs for axisymmetric loading conditions. Critical loads caused by the worst combination of bending and axial loads are assumed to act uniformly around the shell. Figure 24(a) represents a typical Y-ring juncture, and figure 24(b) represents a bulkhead-sidewall juncture for a monocoque structure (cf. figs. 15 and 16). The schematic portion of figures show the various elements of the structural assemblies that are subjected to analysis.

Input data consists of geometry, temperature, and hoop and meridian loads. Elements are divided into short shells, semi-infinite shells, and rings. The effects of axial loads are included in the determination of shell deflections and rotations (ref. 123). The method of analysis is based on matching deflection, rotation, shear, and moment at all element junctions and is fully described in reference 124. Program output includes discontinuity shears, moments, deflections, and rotations at all junctures.



(a) Y-ring

(b) Monocoque

Figure 24. – Structural elements of bulkhead/sidewall junctures subjected to analysis.

2.5.1.4 LOCAL ATTACHMENTS AND OPENINGS

Axisymmetric openings and attachments in the tank structure usually are analyzed by considering the opening or attachment reinforcements to be rings or short thick cylinders. In designs involving nonaxisymmetric openings or attachments that result in noncircular rings, the usual approach is to design a uniform reinforcement for the maximum loads that would exist on an equivalent symmetrically loaded structure. A finite-element computer program (ref. 125) has been developed that will facilitate the analysis of the reinforcing pads, nonaxisymmetric openings, and shell-supported rings when reinforcement thicknesses do not exceed approximately four times the tank wall thickness.

Methods for determining the effects of local loads on tank structure can be found in references 126 through 129.

2.5.2 Structural Dynamics

Tanks such as large integral vehicle tanks must withstand various aerodynamic and acoustically induced loads and environments in addition to service temperature and pressure environments. The smaller internally mounted subsystem tanks usually are intentionally isolated from aerodynamic loads through protective surrounding structure and supports; complete isolation from the dynamic environment, however, is extremely difficult to achieve. In the design of expulsion devices, vibration response, fluid slosh, and acceleration loads are major considerations.

2.5.2.1 BENDING FREQUENCY

Generally, the most significant dynamic problem in vehicle design is the proper control of the body bending frequencies. Bending frequencies influence the aeroelastic behavior of the system, the dynamic loads resulting from wind gust and steady-wind shear, and the interaction of tank bending with the guidance and control system (ref. 130). The importance of bending frequency depends on the location of the particular stage in the vehicle and most often is critical in the center stage.

2.5.2.2 EXTERNAL DYNAMIC ENVIRONMENT

Dynamic bending moments resulting from steady-wind shear gusts and buffeting during flight are influenced by vehicle configuration (e.g., L/D), payload geometry, control system, and the vehicle flight-profile and operating parameters. Transient dynamic loads usually are analyzed to determine whether the loads are more or less than the quasi-static loads determined by rigid-body analysis of gust transients and steady-wind shear and whether the dynamic behavior of the vehicle acts as a gust-load alleviator.

External loading conditions that may induce dynamic response in a tank consist of the acoustical field generated by the engine, aerodynamic or boundary-layer noise, and the loads encountered during transportation and handling. Acoustical and boundary-layer noise must be considered in the analysis.

The dynamic behavior of clustered motors is influenced by the tank stiffness, not only in the overall vehicle dynamic behavior but also in dynamic interaction between the motors. With clustered motors, additional dynamic loading can be generated because of nonsimultaneous motor ignition and burnout, TVC inputs, and aeroelastic conditions. Considerable attention has been given in recent years to the dynamic analysis of clustered structures. At the present time, the analyst has a choice of several procedures (refs. 131 through 134) that include matrix techniques or continuous-mechanics methods.

2.6 TANK FABRICATION

In the design of tanks and particularly the integral propellant tanks for large vehicles, the consideration of fabrication procedures and processes must be continually integrated into the design as it evolves. Present-day production of small- and medium-size subsystem tanks of monocoque design generally involves comparatively routine forging, machining, and welding of two or three tank sections. The fabrication of a sophisticated vehicle structure, however, involves fabrication and assembly of many large structural subassemblies. The major problem is the size of the sections that must be processed. For example, a typical sidewall section of the Saturn S-II LH_2 tank is 103 in. by 325 in. and weighs 7 000 lbm at the start of machining. This large size obviously has significant bearing on machining, forming, handling, and assembly processes.

Machining usually is accomplished by tape-controlled, multihead end mills. Forming a large flat section into a curved segment of a cylinder is a particularly difficult problem if the panel has waffle-type stiffening. Integral circumferential ribs used in the waffle construction create the need to form by a brake forming process. This type of construction is used on the Saturn S-II stage and, initially, resulted in extensive cracking at the rib ends. Where only longitudinal stringers are used, the sidewall section may be mechanically attached to a forming mandrel and heat aged. The weld tooling required for joining large-diameter cylinders is necessarily a major and crucial item if mismatch is to be held to a minimum. Bulkheads are formed by either stretch forming or explosive forming; for a thin-membrane bulkhead, the stretch-forming technique is the most cost effective. To attain further weight reduction, the thin-membrane bulkhead in the Centaur LH_2 tank is chem-milled, thickened areas being left to serve as integral ribs and stringers for structural stiffening. Bulkheads that require stabilization such as that provided by waffle construction generally are formed explosively. In these cases, the ribs are stabilized with a low-melting-point alloy (e.g., Cerrobend) prior to forming. Forming may require two or more stages, with intermediate annealing. Following forming, the sections are solution heat treated and quenched for desired properties. Each of the major fabrication processes presents significant technical problems, and close coordination between production and design presonnel ensures optimum solutions.

2.7 TESTING AND INSPECTION

In tank development programs, testing is used in various phases of tank design, material evaluation, and evaluation of fabrication and inspection processes to establish design requirements, to evaluate alternative approaches, and to verify end results. When designs, structural materials, and fabrication and inspection processes are substantiated on the basis of past experience, testing usually is limited to the degree necessary to certify the new design. When determination of actual strengths and margins is required, destructive testing is employed. The sizes and shapes of destructive-test specimens are virtually limitless, and the specific requirements depend on the particular program needs. The types of destructive tests most frequently used in tank development programs include hydroburst testing (either subscale or full-scale), mechanical-property tests with uniaxial and biaxial specimens, and metallographic and composition analyses.

In addition to extreme care in the design of tanks and accessories, the final product also requires intensive inspection processes to provide the desired confidence. The most common method of establishing and maintaining reliability of a tank is to employ a comprehensive program of process control throughout material procurement and fabrication. This program permits detection of potential causes of failure and timely correction. The degree of success of this method, of course, is totally dependent on the suitability of the inspection criteria.

One of the primary tests imposed on liquid rocket tanks is the proof-pressure test, which has served for many years as one of the final inspections prior to service usage of tanks. During the past ten years, fracture-mechanics studies and aerospace pressure-vessel experience have shown that a properly designed proof-pressure test probably is the most reliable nondestructive inspection method available for ensuring reliable tank service. It is incumbent on the tank designer to ensure that the tank design and the proof-pressure test are compatible, i.e., that the test demonstrates adequate service life of the tank and that no damage is incurred by the tank during test. Procedures for designing an adequate proof test are described in references 3 and 4.

Another reason for performing adequate and well-documented inspection and testing of aerospace tanks is the set of stringent range safety requirements imposed on liquid rocket tanks during checkout and launch of space vehicles.

3. DESIGN CRITERIA and Recommended Practices

3.1 TANK CONFIGURATION

3.1.1 Vehicle-Tank Optimization

Vehicle-tank optimization shall define the minimum-weight tankage structure that will contain the propellants and transmit the launch vehicle loads.

The largest influence on vehicle-tank weight is the material; therefore, tank material should be selected early in the optimization activity. Various tank end closures then should be analyzed to identify the configuration that provides the required fluid capacity with minimum tank weight. Finally, preliminary sidewall designs should be compared in terms of ease of fabrication, past usage history, material size availability, and weight. The various combinations of materials and general bulkhead and sidewall configurations should be compared to identify weight trends and to identify the optimum configuration with greater certainty.

3.1.2 Subsystem-Tank Optimization

Subsystem-tank optimization shall define the minimum-weight tank for the prescribed usage and envelope.

The optimization procedures necessarily involve system configurations. The recommended procedures for the designer are as follows:

(1) Convert the basic rocket-system requirements (e.g., specific impulse) into fluid quantities.

(2) Identify the increases in fluid quantities that must be included to compensate for system-created "losses". In the case of gas pressurant, the resultant loss in volume due to temperature reduction during gas flow must be determined. Accurate solutions of the heat-transfer and energy equations for the majority of stored-gas systems that pressurize (downstream) in a transient-temperature manner are best made in incremental steps during graphical or computer programs. For preliminary design purposes, use much quicker approximation methods for

estimating gas temperature within an associated liquid tank (ref. 135). Consider fluid leakage, ullage space (liquid tanks), expulsion efficiency, filling errors, feedout imbalance, and manufacturing tolerance in the inventory of incremental volumes. Sum these increments and add to the basic tank volumes to obtain total minimum volume.

(3) Use the above-determined tank volume and any imposed installation constraints to compare various geometrical shapes; select the best configuration. Comparison considerations should include the associated tank-supporting bracketry.

3.2 TANK MATERIAL

3.2.1 Mechanical Properties

The values for material mechanical properties used in tank design and analysis, together with the design factor of safety, shall provide an adequate and consistent level of reliability against material yielding and ductile failure.

All design values of material mechanical properties – F_{tu}, F_{ty}, F_{cy}, F_{su}, F_{bru}, and F_{bry} – should be established at consistent levels of reliability that include consideration of both the scatter in material properties and the effects of all processing, environmental, and service variables. Unless special conditions dictate otherwise, the reliability levels used should be similar to the "A" and "B" levels in reference 8. "A" values should be used in the structural analysis of pressure vessels, because these vessels represent single-load-path structures, the failure of which would be catastrophic.

Material design data used in fatigue and creep analyses should be established by methods that take into account both the variation in material properties and the analytical approach to be used.

3.2.1.1 TEMPERATURE EFFECTS ON PROPERTIES

Tank material properties shall be adequate for operational and test loading conditions under all anticipated thermal environments.

The material properties used for the design and analysis of tanks that operate at elevated temperatures must take into account both the temporary effects of increased temperature in reducing properties and, when temperatures are sufficiently high, the permanent strength reductions due to thermal exposure.

The material properties used for design and analysis of tanks that normally operate at cryogenic temperatures must be adequate for all specified and predicted room-temperature operational or test conditions. For many tank applications, it is impractical to take advantage of the higher mechanical properties at cryogenic temperatures, because of the resulting necessity of placing an extra limitation on tank pressures for room-temperature testing or operations and, sometimes, also because of an undesired reduction in the ratio between fracture toughness and material design strength at cryogenic temperatures.

3.2.1.2 FATIGUE STRENGTH

Tank materials shall withstand the specified multiple load cycles.

Tank design, material selection, analysis, and development test programs must take into account the maximum number of pressurization or other load cycles to which the tank might be subjected. Besides service conditions, these cyclic loads should include all proof-pressurization, leak, and operation testing of tank and system both before and after delivery of completed systems. Materials should have adequate low-cycle notched fatigue strength both in parent metal and welds. Stress and strain concentration should be minimized in design and manufacturing, especially in weld areas. Vessel development and qualification test programs should require demonstration of ability to withstand the maximum number of pressure cycles that will be imposed during service life.

3.2.1.3 CREEP

Tank materials shall not deform or rupture as a result of creep.

The possibility of material creep should be considered in all tanks that are pressurized at temperatures above room temperature. Because of the titanium low-temperature creep phenomenon, a creep analysis should be performed on all titanium-alloy tanks. The possibility of creep during testing procedures involving titanium tanks should be considered. Creep should also be checked for aluminum tanks that are pressurized at room temperature for a total duration exceeding 1000 hours.

3.2.1.4 BIAXIAL-STRESS PROPERTIES

Tank material shall withstand the anticipated biaxial loading.

Since the various materials of interest for tank construction do not necessarily behave in accordance with any single, idealized theory of material deformation or failure, it is necessary to evaluate biaxial properties from representative test data. In performing such evaluations, the following factors should be considered:

(1) The stress state used to determine possible biaxial effects in a tank must be the actual stress state at the failure initiation site, including the effects of bending stresses and stress concentrations, if such exist.

(2) High stress concentrations that are critical failure-initiation points can locally obliterate the general biaxial stress field together with its potential effects.

(3) The evaluation of biaxial effects must be concerned with the element or portion of the tank that is actually critical, whether a weld, or weld heat-affected zone, the area around a boss, or any other similar portion.

(4) The biaxial effects observed for initial yielding should not be expected to be the same as those observed for ultimate failure, and vice versa.

3.2.2 Fabrication Considerations

Tank materials shall admit of being fabricated into the necessary configurations and sizes within the limitations of cost and schedule; when fabricated, the materials shall possess the physical properties used in design and analysis.

Manufacturing feasibility studies should be performed to aid in the selection of materials and manufacturing processes that will make possible the production of tanks having the desired configuration, properties, and quality within the limitations of schedule and budget. Such studies should take into account the capacities and capabilities of available equipment for performance of metal forming, machining, welding, heat treating, and other essential processes as compared with requirements for such as indicated by the proposed design, method of fabrication, and material characteristics. The cost and schedule impacts associated with the construction or provision of such facilities that are otherwise unavailable should be considered.

3.2.2.1 SHAPING AND FORMING

Tank material shall, on completion of all deformation processing and other fabrication processing, exhibit acceptable quality and mechanical properties.

The quality and properties of material that has been shaped, formed, or otherwise fabricated into tank components should be verified by a complete testing program for qualification of components. The material chemical composition, structure, soundness, grain size and flow, freedom from defects, and mechanical properties should be verified throughout such components. Provision should be made to provide continuous surveillance of the quality of such components through inspection and testing material provided for this purpose, either integral with the components (e.g., forging trim rings) or, if such cannot be provided, material processed along with components.

3.2.2.2 WELDING

Welded joints in a tank shall exhibit consistent and adequate levels of strength, ductility, and toughness.

Alloys selected for fusion-welded tanks should be suitably weldable and weld reparable under all welding conditions anticipated. Welded joints must have adequate strength, ductility, and toughness at all temperatures at which the tanks are to be pressurized. Materials for which weld joints are considered to have limited ductility should not be used in designs that incorporate (1) longitudinally welded cylindrical sections, (2) domes welded from segments, or (3) welds located in regions of stress or strain concentration (e.g., welded-in bosses and attachments).

To verify that satisfactory levels of joint soundness, freedom from defects, strength, and ductility can be met consistently, weld development studies should be performed to optimize welding conditions for the specific joint materials and geometries contemplated. Weld quality-control procedures must be established to ensure the maintenance of weld property levels and freedom from defects.

3.2.2.3 THERMAL PROCESSING

The material thermal processing requirements shall be satisfiable, within the limitations of budget and schedule, for the sizes and configurations of actual parts or completed tanks. At completion of all thermal processing, tank materials shall exhibit the property levels used in design and analysis.

In selecting materials for tanks, it is necessary to verify that any detailed thermal processing requirements can be met for the sizes and configurations of the actual parts or completed tanks for which such processing is contemplated. The need for such processing may arise from the need for performing various manufacturing operations at low material strength levels or from the need for thermal processing after welding. It is necessary to determine whether the indicated thermal processing can be performed by existing facilities or will require the construction of special facilities.

The material properties and microstructure obtained from heat-treat procedures and facilities should be determined to be satisfactory by thorough destructive and nondestructive testing of material from initial production hardware. Quality-control procedures should be established to maintain all important heat-treatment parameters within the necessary tolerances. Such procedures should include the testing of representative coupons processed together with the parts or completed tanks.

3.2.3 Material Compatibility with Environments

> *Tank materials shall not be degraded unacceptably, become embrittled, or fail prematurely as a result of interaction with aggressive fluids, processes, or environments; and propellants shall not be contaminated or decomposed by reaction with tank materials.*

Alloys must be evaluated for compatibility with the fluids to be contained and external environments to be encountered in service; in addition, evaluation must include all other chemically active or otherwise suspect substances to which materials are exposed during manufacture, storage, testing, and transportation. Substances and processes that are found to be deleterious should not be used on tank materials.

To evaluate proposed alloys and the fluids, processes, or environments to which the alloys are to be subjected, data on the following possible modes of material or system deterioration or adverse reaction may be required:

- Corrosive attack from manufacturing fluids and processes, testing fluids, fluids stored, and atmospheric or other external service environments
- Embrittlement resulting from internal contamination introduced by manufacturing fluids and processes
- Formation of undesirable products of metal/fluid reactions
- Promotion of propellant decomposition (metal/fluid reaction)
- Stress-corrosion cracking
- Galvanic corrosion
- Hydrogen-environment embrittlement
- Material ignition in propellants.

3.2.3.1 SOURCES OF MATERIAL/FLUID REACTIONS

3.2.3.1.1 Manufacturing Fluids and Processes

> *The fluids or processes used during manufacturing operations shall not unacceptably corrode tank material, embrittle it, or otherwise make it susceptible to fracture or to leakage.*

All substances, particularly fluids and fluid processes to be used in contact with high-strength tank alloys during manufacturing operations, storage, or transportation, including the types of materials and processes described previously, should be evaluated for possible incompatibility reactions or effects. This requirement must be observed for titanium alloys and high-strength alloy steels. Previous successful use of fluids or known formulations or processes is one kind of verification data; however, changing conditions of usage can invalidate such experience and require further evaluation, particularly when the danger is internal contamination of material, which cannot normally be determined by nondestructive methods.

The chemical constitutents of all fluid formations or products used on alloys that are sensitive to corrosion or contamination should be known and kept under control. New products considered for use should be investigated for new chemical constituents or markedly different balances of previously used chemicals. The compatibility of new applications of chemicals or formulations, and that of new fluid products for which the chemical constituents cannot be determined, should be verified by appropriate test or investigative procedures before the material is used in contact with high-strength alloys. Contamination of titanium with chloride-containing products or with hydrogen, oxygen, or nitrogen during material processing, heat treatment, or welding must be avoided. Lists of cleaning and processing materials, inspection fluids, testing fluids, and marking and identifying materials that are considered compatible with titanium (on the Apollo program) are provided in reference 34. This reference also contains a list of materials found to be incompatible with titanium.

Processes that are known to contaminate steels with hydrogen must be avoided unless it is certain that effective embrittlement relief can be provided (normally by baking). The sources of hydrogen contamination of steel are discussed in reference 36 (pp. 4 through 8); the elimination of hydrogen from steel is discussed in reference 38. Atmospheres for heat treatment of steel must be selected and controlled to prevent hydrogen contamination, carburization or decarburization, and unwanted scaling.

3.2.3.1.2 Testing Fluids

Fluids used in tank and system testing shall not degrade tank materials or react with them in an unacceptable way.

It is recommended that all fluids to be used in contact with tank materials be maintained free from undesirable contaminants from any source, including decomposition within the fluid. The material threshold stress intensity for crack growth in the proof-testing fluid should be known and taken into consideration in the fracture-mechanics-based safe-life analysis of the tank (sec. 3.2.4.2).

3.2.3.1.3 Stored Fluids

Fluids stored or contained in a tank shall not decompose, deteriorate, become contaminated or react with tank materials in any unacceptable way.

The compatibility of tank materials with fluids to be stored must be verified under conditions of exposure representative of the anticipated service life. The types of test data that may be required to demonstrate absence of material degradation include exposures of both parent metal and welds under stressed and nonstressed conditions. ("Stressed exposure" requirements are discussed further in sections 3.2.3.2 and 3.2.3.3.) The exposure parameters that properly should be represented by substantiating data or experience include exposure temperature, stress, exposure duration, metal heat-treat and surface condition, fluid composition (including the composition range of important constituents), and (possibly) fluid pressure.

Tank materials should be evaluated for possible deteriorating effects on propellants to be stored, either by catalytic decomposition or by other types of metal/fluid reactions. This evaluation is particularly necessary for propellants that tend to be chemically unstable, e.g., hydrogen peroxide.

3.2.3.1.4 Atmospheric and Environmental Corrosion

Tank materials shall not corrode or otherwise deteriorate below allowable limits as a result of exposure to atmosphere or other external environments.

Protection from external corrosion, when required, should be provided in accordance with acceptable guidelines such as those in references 44, 45, 136, and 137, consideration being given to any special environments (such as space environments) or requirements not considered in the referenced documents.

3.2.3.2 TYPES OF MATERIAL/FLUID REACTIONS

3.2.3.2.1 Stress-Corrosion Cracking

Tank materials shall not experience unacceptable stress-corrosion cracking resulting from the effects of sustained stress and exposure to testing fluids, stored fluids, or atmospheric environments.

To prevent stress-corrosion failures, the following guidelines and procedures associated with tank design, manufacture, and testing should be observed:

(1) Tank alloys must be determined to be free from indications of stress corrosion when in contact with fluids to be contained and at stresses up to the material yield strength, in both parent metal (unwelded) and weld areas.

(2) Threshold stress intensities for flaw growth in the fluid to be contained should be considered in the tank safe-life analysis (sect. 3.2.4.2).

(3) Fluids selected for tank and system testing must be known to be free from any tendency to cause stress corrosion when in contact with tank materials.

(4) Materials exposed to atmospheric environments should be resistant to stress corrosion in the environment, as indicated by the absence of cracking tendencies up to a sufficiently high threshold stress.

(5) The exposure of material end grain to an aggressive environment should be avoided, as a general rule, because reduced stress-corrosion resistance in this grain direction is common.

(6) Design details that result in permanent or long-duration high tensile stresses at exposed metal surfaces should be avoided if possible. Examples are interference fits and clamped rigid fittings.

(7) Stress raisers and rough surfaces on exposed surfaces should be avoided.

(8) Fabrication procedures should not result in high unrelieved residual stresses.

(9) Coatings or finishes should not be relied on for stress-corrosion protection until their effectiveness has been established.

3.2.3.2.2 Galvanic Corrosion

Tank materials shall not deteriorate unacceptably or fail as a result of galvanic corrosion.

Galvanically dissimilar metals should not be used in contact or in close proximity in areas exposed to moisture-laden atmosphere. The immersion of such dissimilar metals in water or aqueous solutions should be avoided. The permissible metal couples indicated in references 44 and 45 should be observed.

When it is necessary or desirable to use metal combinations that have a greater galvanic potential difference than permitted by the above references, metal corrosion by galvanic action may be minimized or avoided by observing one or more of the following rules:

(1) Electrically insulate the dissimilar metals from each other, or provide a sufficiently long path for current flow so that the current is attenuated by electric resistance.

(2) Provide suitable coatings to isolate the metals from the fluid. It is important to coat both anode (corroded electrode) and cathode because of the possibility that small defects in the coating will result in unfavorable anode-to-cathode area ratio.

(3) Avoid combinations involving a large cathode area and a small anode area immersed in the electrolyte. In such cases, the rate of attack on the anode will be greatly increased.

(4) When practical, provide chemical inhibitors to the fluid.

Nonaqueous liquids to be stored should be evaluated as to electrical conductivity and development of electrode potentials in contact with the tank metals so that the probability of galvanic corrosion may be established. Such evaluations should take into account all contaminants anticipated.

3.2.3.2.3 Hydrogen-Environment Embrittlement

Tank materials used in hydrogen systems shall not fail as a result of hydrogen-environment embrittlement.

Materials that are to be used in contact with pure hydrogen gas should be evaluated for sensitivity to hydrogen-environment embrittlement. Considerable data on the sensitivity of various alloys to this failure mode are available in the literature (refs. 65 through 68). Materials that do not show the effect or have shown very little sensitivity to hydrogen gas should be selected, particularly for systems in which exposure occurs under pressures greater than one atmosphere. When there is concern as to the possible severity of the effect, the actual materials and forms to be used should be evaluated by obtaining representative test data. In such cases, welds should be evaluated as well as parent metal. In some applications, it may be desirable to use gaseous hydrogen for pressure testing of tanks; this practice will demonstrate the reliability of tanks constructed from high-strength alloys, which may show some sensitivity to a hydrogen environment.

Titanium alloys are not recommended for applications that involve structural loading while the metal is in contact with hydrogen gas at temperatures above −100° F.

3.2.3.2.4 Material Ignition

Propellant tank materials shall not ignite or otherwise react violently in the presence of the propellant.

Titanium and titanium alloys should not be used in contact with oxidizers such as red fuming nitric acid, liquid oxygen, pressurized gaseous oxygen, mixtures of liquid oxygen and liquid fluorine, and other strong oxidizers. The possibility of ignition due to energy pulses from impact, rupture, friction, electricity, heat, or any other source of high localized energy should be considered and evaluated before titanium or titanium alloys are used in contact with oxidizers. Copper, lead, zinc, molybdenum, and many alloys that contain these elements are not compatible with hydrazine and the hydrazine family of propellants. The compatibility of metals with liquid and gaseous phases associated with propellants, particularly the highly reactive propellants, must be established before they are used in contact with such fluids.

The compatibility of any nonmetallic material with a propellant, particularly a strong oxidizer, must be verified by appropriate test data before the material is used in contact with such a fluid.

3.2.4 Fracture Control

Tanks shall have a high reliability against brittle fracture in proof test and in service life.

A complete fracture-mechanics analysis should be performed for each tank to determine material-toughness requirements, to determine flaw sizes that must be discovered nondestructively, and to establish proof-testing requirements (refs. 2, 3, and 4). This analysis should be combined with both an adequately developed program for ensuring repeatable quality in materials processes and manufacturing operations and a system for documenting all information pertinent to a tank's structural performance. Such a program will minimize hardware rejection, minimize failures during proof testing, and provide a suitable level of reliability against brittle failures in service.

Catastrophic failures during proof testing should be minimized by the proper correlation of material toughness in the proof-testing fluid, the material stress at proof pressure, and the flaw-detection capabilities of the applied nondestructive inspection. The largest crack (or crack-like flaw) that potentially could escape nondestructive inspection should be established. The material minimum stress intensity for flaw growth in the proof-testing fluid (either K_{Ic} or K_{TH}) should also be determined. This stress intensity value must be adequate to resist the growth, at the proof stress, of the largest crack escaping detection. If it is not, one or more of the parameters – maximum crack size, material minimum toughness, or proof stress – should be adjusted to obtain reliability against failure in proof test.

Brittle failures during service should be minimized by proper material selection and processing (sec. 3.2.4.1), by the performance of a safe-life analysis (sec. 3.2.4.2), and by implementation of a system of tank documentation, or "pedigree". The documentation maintained for individual tanks should provide material traceability through all manufacturing operations, back to the original material procurement and associated acceptance test results. The results of all inspections performed should be available, together with the details of all repair of rework necessitated. Detailed records of all tank tests or periods of pressurization, including the fluids contained at such times, should complete this documentation.

3.2.4.1 MATERIAL FRACTURE TOUGHNESS

Tank materials shall have adequate fracture toughness; adequate resistance to crack growth under sustained loading in service environments; and known flaw growth characteristics under cyclic loading conditions.

Tank materials should have adequate fracture toughness, under the conditions of use, in both parent metal and welds. Factors that affect this property (e.g., test temperature, test direction with respect to material grain, material variation, and production processing effects) should be taken into account in the selection and evaluation of tank materials. The toughness of actual production material should be verified by performing tests on welded and unwelded material that has been processed in the same way as production parts. Quality control should be provided to ensure adequate toughness in manufactured hardware.

Sustained-load crack growth. – To verify material suitability for the intended use and to allow performance of a complete safe-life analysis (sec. 3.2.4.2), stress intensity values for the growth of cracks under sustained loading in anticipated fluid environments should be obtained for both parent metal and welds. The ratios between stress-intensities for crack growth in the fluids under scrutiny (K_{TH} values) and K_{Ic} values from comparative tests in dry air (or other suitably inert environment) should be computed. Low values of this ratio indicate the possible incompatibility of the material-fluid combination because of stress corrosion or some other mechanism. Such situations should be the occasion for further study of the material-fluid interaction, both for parent metal and for welds.

Cyclic-load crack growth. – The material crack-growth characteristics under cyclic loading in the anticipated fluid environment should be determined, so that crack growth that may occur during repeated pressurization or other cyclic loads after proof testing and before critical service loading can be computed as described in section 3.2.4.2.

3.2.4.2 SAFE-LIFE ANALYSIS

A safe-life analysis based on fracture mechanics shall verify tank reliability in service.

The data utilized for this computation should include the stress intensity for crack growth in the material in the service fluid and at the service temperature, the cyclic crack-growth characteristics in the environments anticipated for such loading cycles, the (typical) critical stress intensity applicable to proof-testing conditions, and the material stresses associated with service, cyclic loading, and proof testing. At present, it is considered unconservative to use minimum values for the material critical stress intensity when computing the largest crack that can exist in a tank after proof test and that can then grow during cyclic loading. Typical K_{Ic} values are more realistic for this computation and for use in determining the service K_{TH}, an appropriate value for the ratio K_{TH}/K_{Ic} being selected from current published data for the material under consideration.

The possibility of significant subcritical crack growth during the proof-test cycle should be investigated, because of the potential effect on the ability of the safe-life analysis to guarantee tank reliability. This requirement applies particularly to low- and medium-strength materials that have good toughness.

3.2.4.3 ADDITIONAL ELEMENTS IN A FRACTURE-CONTROL PROGRAM

Quality control, qualification testing, and documentation are treated in section 3.2.4.

3.3 TANK STRUCTURAL DESIGN

3.3.1 Safety Factor

The safety factor for vehicle- and subsystem-tank structure shall be the minimum required to obtain the desired reliability.

Within the current state of the art, it is not considered advisable to recommend a specific value of design safety factor. The design safety factor should be based on the reliability requirements of the specific program. However, certain guidelines are recommended, as follows:

(1) A base factor of safety should be established for both vehicle and subsystem tanks. Variations from the base should be justified on the basis of a thorough knowledge (supported by tests, as required) of the failure mode and the cost, weight, and reliability effects of these variations in the base factors of safety.

(2) Instability modes of failure (e.g., bulkhead failure under collapsing pressures, or tank sidewall general instability failure under tank wall compressive loads) should have a design factor of safety greater than base. For pressure-stabilized monocoque sidewalls such as those in the Atlas vehicle and for situations where the primary loading condition is a bending load, postbuckling strength should be considered in the determination of a safety factor. Stable, tension modes of failure (e.g., burst pressure failure of tank membrane or bulkheads) may have design factors of safety less than base.

(3) Welds should have a factor of safety greater than base, because of the inconsistency in the welding process, variations in the presence and size of defects, and the high cost of inspection and repair coupled with the small weight penalty incurred.

(4) Factors of safety should be applied to strain, rather than to stress, in those areas where the material inevitably is stressed locally into the plastic range or where the weight penalty to preclude plastic behavior (ref. 122) would be excessive (e.g., the membrane material immediately adjacent to local "hard spots" - areas of greatly increased thickness).

(5) For non-ASME-coded tanks, the test programs and quality requirements should be established to satisfy the Range Safety Criteria.

3.3.2 Loads Analysis

The tank loads profile shall include all individual design loads or the worst combination thereof.

All axisymmetric and local design loads, including dynamic loads, should be resolved into membrane loads to determine the critical load condition. The critical membrane loading condition should be expressed in terms of a load-temperature-time profile. This profile should be prepared by plotting all loads and associated temperatures imposed (during handling, storage, assembly, installation, and service use) versus time. The worst combination of loads as indicated by the profile then should be used in the design structural analysis. The load considerations for subsystem tanks internally mounted within a vehicle should include internal pressure, loads at supports, and related interface plumbing as amplified by the expected vibration, acceleration, and other flight environments. The load considerations for integral vehicle tanks should include internal pressure, compressive loads from weight of the upper vehicles under flight conditions, side loads due to thrust misalignment during vehicle direction changes, and local membrane loads imposed by associated feed, vent, and service lines under flight conditions.

3.3.2.1 TANK SIDEWALL

The loads profile for tank sidewalls shall include pressure, inertial force, axial loads, and bending moments.

Ultimate design tension loadings in the longitudinal direction should be determined by combining ultimate loading due to body axial load and bending moment with ultimate loading from ullage and head pressure. The ultimate design compressive loading should be determined by combining ultimate loading due to body axial load and bending with loading from tank ullage and head pressure; use methods such as those presented in reference 96.

3.3.2.2 END CLOSURE

The loads profile for tank end closures shall include the effect of pressure and geometry.

The bulkhead geometry should be considered as a means of reducing the hoop loads at the tank wall junction. These reduced hoop loads minimize future problems resulting from high stresses in the juncture. Loading should be determined by methods such as those presented in reference 97.

3.3.2.3 INTERTANK BULKHEAD

The loads profile for intertank bulkheads shall include the effect of pressure differentials (burst and collapse) and temperature gradients.

The effects of pressure and temperature differentials on common bulkheads should be determined. The loadings should include maximum temperature gradients produced during the tank fill operation when both tanks contain cryogenic fluids. An internal-loads analysis such as the program for a multilayered shell of revolution described in references 98 and 99 should be performed.

When separate membranes are involved, treat the individual bulkheads as end closures (sec. 3.3.2.2).

3.3.2.4 ATTACHMENT

Attachment loads shall include the radial load, moment, and torque imposed by attachment subsystem.

A loads analysis should be performed to establish the magnitude of loads imposed by attached structure, i.e., line systems, valves, disconnects, and similar attachments. Because of the complexity of these dynamic analyses, it is recommended that a dynamic-response computer program be used to calculate loads. See reference 138 for a typical analytical method.

3.3.3 Membrane Thickness

The tank membrane thickness shall be the minimum consistent with usage conditions, reliability requirements, and fabrication limitations.

For the conventional tank shapes such as spheres and cylinders, use standard formulas (ref. 100, pp. 299-307) for calculating membrane thickness based on the tank loads (pressure), shape, and material properties in the expected environments. Apply the factor of safety to the limit load and establish membrane thickness by using the equations for meridional and hoop stresses. The greater thickness resulting from use of these equations establishes the minimum membrane dimension for the intended pressure/environment usage. The membrane thickness requirements to preclude unacceptable flaw growth (sec. 3.2.4) then should be determined. The larger membrane thickness is the dimension to be used for design.

3.3.4 Sidewall

Vehicle-tank sidewall structure shall be capable of transmitting the required loads while containing a given liquid under stated conditions of acceleration, pressure, and flight environment.

The recommended procedure for selecting the optimum sidewall configuration is to perform a trade study along the lines indicated in table VIII. Each item is given a point value representing an assessment of the relative importance of the item. Each candidate configuration then is evaluated on how well it rates on each item compared with the maximum number allowed for that item. The largest total sum for a given candidate indicates the most desirable configuration. It should be demonstrated that the selected sidewall design is consistent with the requirements for structural attachment and will withstand the stress imposed by the bulkhead on the sidewall.

3.3.4.1 SKIN-STRINGER-FRAME

Skin-stringer-frame construction for tank sidewalls shall transmit axial loads without buckling.

Skin-stringer-frame construction should be used when large axial loads (e.g., those in the Saturn IC booster) are applied to the tank sidewall. Trade studies should be conducted to establish the optimum stringer configuration (blade vs T-stringer). Integrally machined stringers are preferable because they preclude the need for mechanical attachments that penetrate the skin and create potential leak paths and stress raisers.

3.3.4.2 WAFFLE

Waffle construction for tank sidewalls shall transmit axial loads and bending moments without buckling.

When axial compressive loads are of moderate magnitude (e.g., those in the Saturn S-IV-B stage), waffle construction should be employed. In addition, because of its ability to resist buckling during compressive loadings, waffle construction should be considered when insulation is required. However, waffle construction is not recommended for pure membrane loadings as developed in subsystem tanks.

Table VIII. – Sample Trade Study for Selection of Optimum Sidewall Configuration

Tradeoff factor	Point Value	Rating of configuration		
		I	II	III
Technical				
Weight	100			
Safety	30			
Reliability	40			
State of the art	30			
Qual./verif. testing	40			
Impact on other systems	20			
Growth potential	30			
Anticipated problems	20			
Performance	40			
Subtotal	350			
Fabrication				
Ease of manufacture	45			
Fab. state of the art	35			
Inspection capability	15			
Facilities impact	30			
Hardware availability	25			
Subtotal	150			
Operations				
Service equipment impact	50			
Maintainability	30			
Checkout impact	20			
Launch facilities impact	50			
Subtotal	150			
Cost/schedule				
Nonrecurring costs	50			
Recurring costs	150			
Schedule compatibility	150			
Subtotal	350			
Total score	1,000			

3.3.4.3 MONOCOQUE

Pressure-stabilized monocoque construction for tank sidewalls shall transmit axial loads without buckling.

Pressure-stabilized monocoque tanks should be considered when axial loads are less than bending loads. The membrane can be allowed to buckle partially above limit load if bending is the predominant loading (ref. 122). Consideration should be given to methods of supporting the structure when the tank is unpressurized.

3.3.5 End Closure

Tank end closures and intertank bulkheads shall provide required tank fluid capacity and structural capability within target weight and height.

In determining the optimum bulkhead height, consideration should be given to the following factors:

- Effect of changes in tank height on overall vehicle bending moments
- The desirability, from a manufacturing and reliability standpoint, of using the same bulkhead shape throughout a given stage
- Bulkhead deflection under load
- Bulkhead ability to sustain its own weight or other external loads without collapsing
- Other system space requrements between the bulkhead and skirt (e.g., space needed for black boxes).

Specific practices for achieving optimum design are set forth in sections 3.3.5.1 through 3.3.5.3 below.

3.3.5.1 FORWARD BULKHEAD

Forward bulkhead geometry shall be optimized with adjoining structure to minimize vehicle height and weight.

The following procedure outlines the recommended method for determining the bulkhead height that results in the minimum total weight design:

(1) Studies of various bulkhead shapes should be made, and a curve of bulkhead weight vs height constructed for each shape. It is recommended that only those shapes that preclude hoop compressive stresses be considered.

(2) The skirt structure should be optimized for the design running load, and its weight per inch of length computed.

(3) The tank structure should be similarly treated, and again a weight per inch of length computed.

(4) The optimum height to achieve minimum total weight of skirt, bulkhead, and tank wall to contain a fixed volume then should be determined by plotting a curve of total weight vs height (fig. 11).

3.3.5.2 AFT BULKHEAD

Aft bulkheads shall withstand the internal loads resulting from pressure, acceleration, and the attachment of engines and system components.

The large pressure differential measured from the apex to the equator of an aft bulkhead dictates the requirement for a compressive stable design in the equatorial region. Waffle-type structure is recommended in the areas of compressive loads; monocoque construction is recommended in the noncompressive loads area. A pressure-stabilized aft bulkhead may carry engine thrust loads if internal support structure to distribute the load is provided; a semimonocoque structure with an internal thrust barrel as used in the Centaur vehicle is a good approach.

3.3.5.3 INTERTANK BULKHEAD

An intertank bulkhead shall impose minimum weight on the vehicle tanks.

The intertank bulkhead should be shape optimized to minimize total vehicle weight in the same manner as the forward bulkhead, as described in section 3.3.5.1.

When extremely lightweight design is necessary and no insulation between fluid tanks is required, the single-membrane divided bulkhead is recommended. Since the single membrane has structural capability only under tensile loads, the use must be weighed against reliability requirements and the undesirability of operational restrictions.

If insulation is required, an insulation bulkhead can be attached adjacent to the structural bulkhead to form a cavity, as shown in figure 22. The cavity may be filled with insulation or may be a vacuum chamber. When vehicle-tankage length is restricted severely, a sandwich-type common bulkhead is recommended. This construction will reduce stage length up to one-third of tank diameter, but the benefit should be weighed against increased fabrication complexity of the bulkhead and the bulkhead-to-sidewall juncture.

3.3.5.3.1 Sandwich Construction

Sandwich construction used in bulkhead design shall withstand tank pressures, temperature differentials, and tank fluid loads.

Sandwich construction (fig. 10) should be optimized to establish the proper core type, size, and depth and the facing-sheet thicknesses. Reference 102 defines methods that may be used for this optimization. Consideration should be given to joint design and attachment provision when honeycomb sandwich construction is selected as the bulkhead material.

3.3.6 Attachment Junctures

3.3.6.1 WELD JOINTS

Weld joints in tank structure shall result in minimum heat-affected zone, shall require minimum postweld cleaning, and shall maintain structural continuity under all conditions of loading.

The circumferential welds should be removed as far as possible from the bulkhead-sidewall intersection so that bending stresses at the discontinuity are attenuated. The weld joint should be designed to operate at a stress and strain level that minimizes the need for repairs, due consideration being given to the probable ranges of porosity and inclusions that normally result from welding.

Structural weld joints in tank structure should be butt welded; however, lap-seam welds with backup rows of spot welds may be used, as was done on the thinwalled Atlas and Centaur tanks. The preweld joint configuration should be established through consideration of membrane material and basic thickness. Recommendation of specific configurations is inadvisable because of variations from design to design. It is appropriate, however, to list the following guidelines that have provided successful designs:

(1) Backup rings to prevent dropthrough should be avoided because of resultant contaminant traps and difficulty of contamination removal.

(2) For subsystem tanks of monocoque design with a membrane thickness of 0.030 in. and less, burndown butt joints are recommended.

(3) For subsystem tanks of monocoque design with a membrane thickness greater than 0.030 in., a groove and filler-wire joint is recommended.

(4) For thin-walled tanks up to 18 in. diameter, the weld-joint transition (taper) length on both sides of the weld centerline should cover an arc of at least 30° originating at the tank centerline (fig. 25).

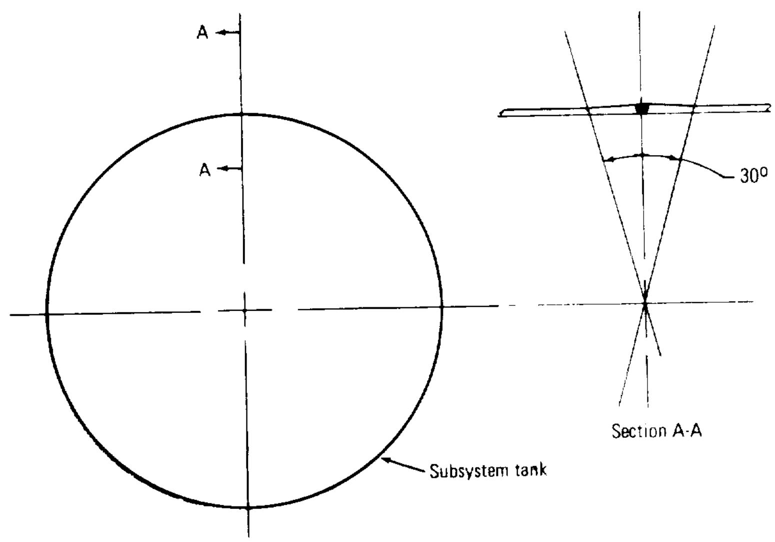


Figure 25. – Sketch of geometry of a weld joint for a subsystem tank.

(5) Where possible, weld lines should be located so that the joint transition (taper) does not extend into the hemispherical section.

(6) On subsystem tanks where the exterior skin surface need not be smooth, the majority of the transition material should be outside the membrane median line so that weld joint "sink in" is offset.

(7) Weld lands should be joined to the basic tank membrane by liberal transition sections and fillet radii (fig. 13(b)).

3.3.6.2 BULKHEAD/SIDEWALL JUNCTURE

Attachment junctures shall provide reliable, leakproof paths for the loads from the connecting major components (skirts, tank sidewalls, and bulkhead) and shall minimize discontinuity stresses.

Welding the tankage enclosure is the best way to avoid leakage. Y-ring designs shown in figure 15 are recommended for avoiding leakage and providing an efficient structural load path. There should be sufficient material in the Y-ring itself to preclude excessive hoop tension stresses in the meridional weld.

Bulkhead membrane thickness and tank stringers should be tapered as they approach the circumferential welds, so that bending moments caused by eccentricities are reduced. Eccentricities in the skirt-to-Y-ring outer leg also should be minimized.

Rigorous analysis of major junctures must be verified by testing under all critical design loading conditions.

Because of the difficulty of repair, the undesirability of tank reentry and cleaning, the necessity of postrepair retesting, and the schedule impact caused by replacement of parts where further weld repair is not feasible, it is highly recommended that weld design be very conservative.

3.3.6.3 BOSSES AND SUPPORT PROVISIONS

Tank bosses and support provisions shall impose minimum discontinuities in the tank membranes.

Structure for attachments should be integral and smoothly blended into the basic tank membrane so that stress and strain concentration are minimized. Two configurations are shown in figure 26, configuration B being the recommended design. Fillet radii should be large, and transition pads liberal and preferably tapered. An alternate approach is the welded-in pad or ring; however, the design choice of a welded-in ring versus an integrally milled ring for membrane bulkheads should be evaluated carefully for each particular application, the reliability and freedom-from-repair characteristics of the integral design being balanced against the general acceptability and much lower cost of the welded-in design.

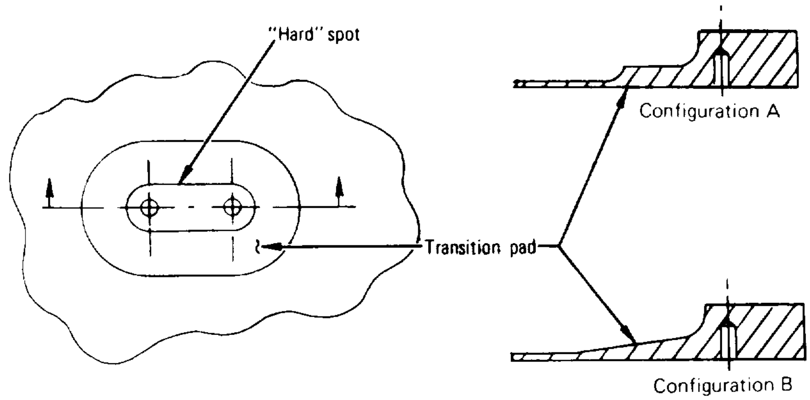


Figure 26. – Two configurations of structure for attachments to a tank.

3.3.7 Openings and Access Doors

Tank openings and access doors shall limit leakage to acceptable levels and shall result in minimum additional local stresses and strains on the tank.

The bolt attach ring and adjoining portion of the door or tank opening should be designed to minimize joint rotation and to match as nearly as possible the deflection of the tank structure if no opening existed. The effects of eccentricities in flange load should be minimized by tapered or stepped transition sections.

Because each new tank design usually has its own unique port requirements, it is inadvisable to recommend specific configurations. Good design practices, however, require consideration of certain guidelines applicable to all configurations, as follows:

(1) Ports should be integral with the tank membranes.

(2) Threaded bosses should be employed as a tank opening where possible to minimize discontinuities in tank membranes.

(3) On threaded bosses in thin-walled tanks up to 18 in. diameter, the transition (taper) length should be at least as long as an arc within a 20° angle originating at the tank centerline (fig. 27).

(4) Threaded bosses should have external wrenching pads to facilitate installation of mating fittings.

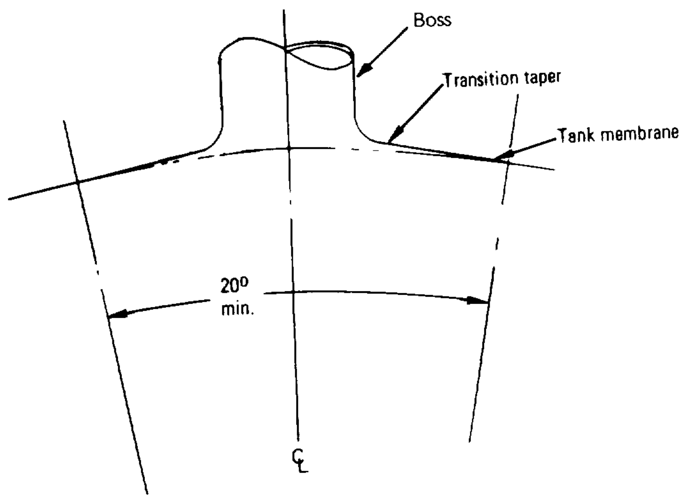


Figure 27. – Recommended geometry for transition from boss to tank membrane.

(5) Ports should be as large as possible to facilitate inspection of the tank interior.

(6) Closures for access openings should be made of material with quality equivalent to the tank material.

(7) Closures for access openings should minimize bending in the adjacent tank membrane.

(8) Tank port provisions should be located and designed to simplify forging dies.

(9) Threaded inserts should have bolt locking provisions, and the bolting flanges should be capable of repair in the event of thread damage.

3.4 TANK COMPONENTS

3.4.1 Propellant Slosh and Vortex Suppression Devices

Baffle configuration and location shall prevent adverse liquid motion.

General recommendations for baffle configuration are not possible since various approaches appear to work satisfactorily for a particular condition. A comprehensive study of slosh suppression and slosh loads is presented in references 103 and 139, respectively. Two basic guidelines are as follows:

(1) In a vehicle with a requirement for multiple engine starts, the baffles should be installed in the tank at a position slightly below the anticipated surface level of the liquid at the time that suppression is required (e.g., at engine cutoff).

(2) Vanes or baffles should be located around a tank fluid exit such that fluid swirling is disrupted without causing cavitation of the downstream pump.

3.4.2 Propellant Positioning Devices

The propellant positioning device shall provide the required liquid control under flight environments and conditions, and its weight and volume shall be minimal.

The propellant positioning device should have the required structural capability and rigidity to withstand the dynamic loads imposed by propellant behavior and by flight environments. The design should have minimum impact on the associated tank design in terms of installation and removal needs and support requirements within the tank.

The propellant positioning device should be capable of being cleaned, flushed, and dried when fully assembled in the tank.

The screen mesh size should be as large as possible to facilitate manufacturing and cleaning and to minimize the possibility of hole clogging by particulate contamination.

Partial-fluid-control devices should be sized and located so that the propellant quantity retained will sustain engine firing sufficiently long to ensure propellant settling within the tank.

3.4.3 Propellant Expulsion Devices

The expulsion device shall continuously maintain the fluid to be expelled at the tank outlet under all conditions when outflow is required.

Selection of an expulsion device should be based upon consideration of the tank size, weight constraints, and expected usage. The tank mountings and the expulsion-device attachment points should be as closely coincident as possible to minimize vibration amplification into the expulsion device.

Expulsion devices that contain the fluid should be capable of evacuation preparatory to fluid servicing, or the tank must be oriented with a vent port oriented upward.

If a bladder-type device is to be used in vertically mounted cylindrical tanks, a slightly undersize cylindrical section in the bladder to reduce frictional drag between the bladder and tank wall should be considered.

3.4.3.1 EXPULSION EFFICIENCY

The expulsion device shall have maximum expulsion efficiency.

For maximum expulsion efficiency, the liquid to be expelled should be contained within the device. If a flexible bladder is used, the central feedout tube should be as small as possible to minimize fluid quantity that the bladder cannot expel. It is recommended that the tube be designed as a long flexible spring, so that under "g" forces it can follow the motions of the fluid. The tube flow area also should be sized to introduce negligible flow resistance.

If a metal device is used, it should be designed with nesting convolutes to minimize residual fluid that may remain lodged in each convolute. The moving closeout head of the bellows should be designed to nest into the tank contour to improve volumetric efficiency of the tank system.

For piston-type devices, the piston seals should be designed for reliability against particulate contamination, wear, and fluid damage, so that negligible leakage will occur during service life.

The pressure required to actuate the expulsion device fully should be as low as possible so that consistent fluid flow throughout the expulsion cycle is ensured.

3.4.3.2 MATERIAL

The expulsion-device material shall satisfy all compatibility, leakage, and temperature requirements and shall be of minimum weight.

No single material is suitable for all expulsion-device applications. To select the optimum material, the designer must identify all operating conditions in the order of their significance. The material that can withstand or fulfill the most usage requirements usually is the proper choice. It can be seen, however, that establishing the comparative importance of the various usage conditions depends heavily on the judgement of the designer.

Selection of material for an expulsion device must take into account the interrelation of the functional and environmental requirements and the material characteristics. For extended missions or usage periods (e.g., ten years) compatibility and resistance to permeation should have more significance in material selection than, for example, ease of fabrication. For extremely cold or warm environments, the selection should be based heavily on material resistance to degradation at temperature extremes.

If permeation of liquid vapors and pressurant gas across the expulsion device is unacceptable to upstream system components or engine operation, a positive barrier device such as a metal bellows or diaphragm or bladder with a metallic barrier should be used.

The designer should ensure that the material selected is compatible with all fluids that will be used throughout the life of the expulsion device. Particular emphasis should be placed on the assessment of fluids that may be employed while the device is subjected to operating stresses.

3.4.3.3 DESIGN MARGIN

The expulsion device shall have an adequate capability beyond the intended operational functions and service environment conditions.

Establishment of a combined operational and environmental program for demonstration of the design margin of an expulsion device requires caution and judgement on the part of the designer. The imposition of combined requirements that are unrealistically severe and damaging to the expulsion device should be avoided. A liberal margin should be imposed only on those requirements that have a high degree of uncertainty. For example, the fill and expulsion cycles can be predicted with reasonable accuracy and, therefore, cycle requirements beyond anticipated usage should be minimized. Mission temperature and vibration specifications, on the other hand, usually have a degree of uncertainty during the development phase, and a requirement for demonstrating a more liberal margin in these areas is justified.

The possible effects of combined operational and environmental conditions such as full working pressure at elevated temperature should be evaluated so that premature and probably uninformative failure is precluded. The designer should also attempt to evaluate the added affect of gravity on expulsion device performance when the margin-demonstration tests are conducted. This precaution is particularly significant for horizontally mounted cylindrical tanks that employ bladder-type expulsion devices.

3.4.4 Tank Insulation

Tank insulation shall withstand the tank strains resulting from temperature, pressure, and vehicle body loads.

The selection of an insulation system for cryogenic tank application should consider the magnitude of the applied strains. When strain levels are high, spray foam or bolted insulation is recommended. To avoid the possibility of insulation damage from ice formation and from handling, internal insulation should be used when the improved material properties at cryogenic temperatures are not involved in the attempt to achieve minimum weight. Methods for repairing localized insulation damage should be included in the insulation design considerations.

3.5 TANK DESIGN ANALYSIS

A design analysis shall verify the structural acceptability of the tank design.

Both structural and dynamic analyses should be performed concurrently with the design. Consideration should be given to tensile and compressive stresses arising from pressure loads, thermal loads, and static and dynamic loads, particular attention being given to major junctures and local attachments and openings.

3.5.1 Strength Analysis

Analysis by accepted analytical techniques shall verify tank structural integrity for all critical flight and ground conditions.

Margins of safety should be computed and specified for all structural elements. The analytical methods used should be conservative to the extent of the uncertainties in the analytical methods or the manufacturing processes. All assumptions should be clearly stated, and extreme caution should be exercised in the formulation of the analytical model used to simulate the actual structure, especially if analysis is performed by computer. Areas that require verification by testing should be so indicated. The analysis should include determination of the effects of combined loading as well as cyclic and sustained loading.

3.5.1.1 TENSION-LOADED STRUCTURE

Tensile stresses and deflections in the shell structure shall not exceed allowable values for yield and rupture under the combined loads for all critical design conditions.

Deflection calculations should be based on nominal material thickness. For yield and ultimate stress calculations, minimum thickness should be used.

Analysis of welds should be empirical and based on test results for the particular weld land configuration being used. Test procedures must be determined carefully so that both the test-specimen fabrication and loadings represent a proper simulation of real hardware. Because of the difficulty and expense in performing biaxial tests, it is highly recommended that a realistic set of weld specifications be firmly established early in a program so that design allowables for welds and weld repairs are consistent with fabrication, inspection, and repair procedures on the actual hardware.

3.5.1.2 COMPRESSION-LOADED STRUCTURE

Compressive stresses on the shell structure shall not exceed allowable values for yield and buckling under the combined loads for all critical design conditions.

The analytical calculations should be based on nominal dimensions. In general, instability computations should reflect conservative values and should be followed by full-scale testing that simulates the critical biaxial load and thermal conditions.

3.5.1.3 MAJOR JUNCTURES

Discontinuity stresses from critical combined bending and axial loads at tank major junctures shall not exceed material allowables for rupture.

The analysis should include all elements that make up a juncture and should be based on normal material tolerances. Analysis should confirm that circumferential welds are located in regions where joint discontinuity stresses are minimum; if not, sufficient material should be provided to reduce the discontinuity effect.

3.5.1.4 LOCAL ATTACHMENTS AND OPENINGS

The design stress at membrane local attachments and openings shall not exceed the allowable yield or ultimate stress.

A finite-element computer program similar to that shown in reference 125 is recommended for the analysis of the reinforced openings and pads. This computer program will handle a shell structure of arbitrary geometry and loading. A qualification test of typical openings and attachments should be performed to verify the design.

3.5.2 Structural Dynamics

The tank structure shall withstand all transient and steady-state dynamic loads or the worst combination of dynamic loads and critical static loads.

Detailed dynamic analysis of the particular stage and the vehicle should be performed to ensure that the tank's design is adequate for all imposed transient and steady-state dynamic loads. The dynamic loads imposed on the tank as determined from the individual dynamic analysis should be integrated into the vehicle structural analysis. The axial, shear, and bending distribution resulting from transient dynamic loading conditions should be compared with equivalent static loading conditions and should be included in the vehicle load-time-temperature-history profile. The transient dynamic stresses should be combined with any static or steady-state vibratory stresses when applicable.

Recommendations for specific methods of analysis for all dynamic conditions are beyond the scope of this monograph; however, dynamic analysis techniques that may be used are discussed in references 140 through 143.

For dynamic analysis of clustered structures, matrix techniques or continuous-mechanics methods (refs. 131 through 134 and 144 through 147) may be used.

3.5.2.1 BENDING FREQUENCY

The tank body bending frequency shall be within the limits imposed by the vehicle flight control system or by predicted transient dynamic loads.

The vehicle-tank stiffness, including EI, GJ, and AE distributions, where

E = modulus of elasticity

I = moment of inertia

G = modulus of rigidity

J = torsion constant

A = area of cross section

should be defined and used in the dynamic-model analysis of the vehicle.

Vehicle-tank stiffness should be consistent with the minimum stiffness required to ensure stable aeroelastic behavior of the vehicle, to ensure structural adequacy under transient dynamic loads, and to limit the body-bending frequencies to within the capabilities of the guidance and control systems (refs. 148 and 149).

3.5.2.2 EXTERNAL DYNAMIC ENVIRONMENT

Tanks shall withstand the maximum transient longitudinal and transverse flight loads and the shipping and handling loads.

The dynamic analysis for these conditions should include the dynamic characteristics of the portion of vehicle remaining at any point in flight and the characteristics of the test stand when applicable.

The determination of the shear and bending dynamic loads should include the vehicle dynamic characteristics (natural frequency in bending) and the harmonic content of the forcing function. Analysis of dynamic interaction among the guidance and control system, the TVC system, and the vehicle also should be included.

Procedures for shipping and handling of vehicles should require suitable packaging and harness supports to limit the transient dynamic loads imposed during handling and shipping to within the load capability of the vehicle tank as designed for flight. The dynamic characteristics of any suspension system and any shock or vibration mitigation systems included in the handling equipment or shipping container should be included in the dynamic analysis of the tank for transportation and handling environments.

3.6 TANK FABRICATION

The tank and component fabrication processes shall be the most reliable, the least time consuming, and the most cost effective for the particular tank and program needs.

An engineering study of fabrication processes should he accomplished to select the fabrication processes that afford the best compromise between fabrication schedule and costs without reducing reliability below specified levels. The engineering study should include detailed tradeoff evaluations of fabrication and welding processes; past experience with and reliability of the various processes; schedule effect of the processing; and fabrication, tooling, and facility costs versus the tank configuration.

Fabrication processes should be selected carefully to avoid harmful effect on the material and end product. This selection requires a detailed analysis of the effect that fabrication processes will have on the material and the completed tanks. If not available, information on process effects should be developed in a material- and process-evaluation program.

3.7 TESTING AND INSPECTION

Testing shall be adequate to evaluate the basic tank design, and the inspection processes shall be capable of detecting the unacceptable defects in tank materials and in the fabricated tank.

It is not possible to make across-the-board testing recommendations, since each tank program has its own design and usage conditions that dictate unique testing. Destructive testing of full-scale tanks, particularly of large vehicle tanks, often is prohibitive from a cost standpoint. However, destructive testing of properly designed subscale tanks should be conducted when necessary for evaluating the full-scale tank. Subscale test tanks must be designed to duplicate the following parameters of the full-scale tank:

- The wall thickness (burst stress on the subscale membrane equal to the expected burst stress of the full-scale case)
- Production materials
- Production methods and processes
- Inspection methods

The tank proof test should be designed on the basis of fracture-mechanics theory (sec. 3.2.4). Test pressure, test temperature, external axial and bending loads, and pressurization rates should be in accordance with specific program requirements.

Inspection processes should be employed throughout the tank program beginning with material procurement and continuing through fabrication, process control, and final acceptance. Each phase can use different inspection techniques with different acceptance or rejection standards. For this reason, an overall master plan for the use and management of the quality-control program should be established prior to the start of fabrication. The scope of the master plan should be established on the basis of the required reliability level, the type and orientation of defects encountered, and the process sensitivity required.

APPENDIX A

Conversion of U.S. Customary Units to SI Units

Physical quantity	U.S. customary unit	SI unit	Conversion factor[a]
Density	lbm/in.^{3}	kg/m^3	2.768×10^4
Energy	ft-lbf	N-m	1.356
Force	lbf	N	4.448
Fracture toughness	ksi-in.$^{1/2}$	(N/m^2)-m$^{1/2}$	1.099×10^6
Length	in.	cm	2.54
	mil	μm	25.4
Mass	lbm	kg	0.4536
Pressure	atm	N/m^2	1.013×10^5
	psi (lbf/in.^{2})	N/m^2	6895
	ksi (1000 psi)	N/m^2	6.895×10^6
Temperature	°F	K	$K = \frac{5}{9}(°F + 459.67)$
Tensile stress	ksi	N/m^2	6.895×10^6
Volume	ft^3	m^3	28.32×10^{-3}
	gal	m^3	3.785×10^{-3}
Yield strength	ksi	N/m^2	6.895×10^6

[a]Multiply value given in U.S. customary unit by conversion factor to obtain equivalent value in SI unit. For a complete listing of conversion factors, see Mechtly, E. A.: The International System of Units. Physical Constants and Conversion Factors. Second Revision, NASA SP-7012, 1973.

APPENDIX B
GLOSSARY

Term or Symbol	Definition
A	area of cross section
ACS	attitude control system
APS	auxiliary propulsion system
a	crack dimension of primary interest (usually, maximum crack depth)
a_{cr}	critical crack dimension for unstable propagation at a given stress
a_i	initial crack dimension
allowable load (or stress)	load (or stress) that, if exceeded, produces tank failure. Failure may be defined as buckling, yield, or ultimate, whichever condition prevents the tank from performing its function.
alpha	designation for the microstructure of titanium and its alloys when the structure is hexagonal close-packed
beta	designation for the microstructure of titanium and its alloys when the structure is body-centered cubic
C	material constant in evaluating crack growth
CM	command module (Apollo spacecraft)
c	one-half the length of a part-through crack
Charpy impact strength	impact strength measured in a test in which a notched bar (of specified dimensions) is struck by a swinging pendulum; the energy absorbed in the fracture is measured. A striking velocity of 17.5 ft/sec is employed; test values are given in ft-lbf
combined stresses	stresses resulting from simultaneous action of all loads to which a structure is subject
coupon	a piece of metal representative of a batch, mill run, or lot, from which a metallurgical test specimen is prepared

Term or Symbol	Definition
creep	slow but continuous deformation of a material under constant load or prolonged stress
cryogenic	fluids or conditions at low temperatures, usually at or below $-150°$ C
d	weld land width
delta	a change in a quantity (e.g., an increase in volume)
design burst pressure	maximum limit pressure multiplied by the ultimate factor of safety
design safety factor	an appropriate arbitrary multiplier greater than 1 applied in design to account for design contingencies such as slight variations in material properties, fabrication quality, load magnitude, and load distributions within the tank structure
design ultimate load	limit load multiplied by the ultimate design safety factor
design yield load	limit load multiplied by the yield design safety factor
E	modulus of elasticity
ELI	extra low interstitial
FH	full hard temper
F_{bru}	design ultimate bearing strength
F_{bry}	design bearing yield strength
F_{cy}	design compressive yield strength
F_{su}	design ultimate shear strength
F_{tu}	design ultimate tensile strength
F_{ty}	design tensile yield strength
G	modulus of rigidity
g	acceleration due to gravity

Term or Symbol	Definition
HAZ	heat-affected zone
I	moment of inertia
J	torsion constant
K	crack-tip stress-intensity factor
K_c	critical stress-intensity factor
K_{Ic}	stress intensity for initiation of unstable crack growth under conditions of maximum constraint as in thick sections (plane-strain fracture toughness)
K_{TH}	threshold stress intensity: highest stress intensity for which there is no crack growth under sustained load in a given environment
L/D	length-to-diameter ratio
limit load	maximum expected load that will be experienced by the tank structure under the specified conditions of operation, with allowance for statistical variation
limit pressure	maximum pressure that will be experienced by the tank structure under specified conditions of operation. Maximum limit pressure is the maximum vent valve pressure plus hydrostatic head (if applicable); minimum limit pressure is taken as the minimum operating pressure of the tank under the specified conditions of operation, plus hydrostatic head (if applicable).
margin of safety (MS)	fraction by which the allowable load or stress exceeds the applied load or stress, $MS = \frac{1}{R} - 1$
membrane	tank skin or shell
n	material constant in evaluating crack growth
NDI	nondestructive inspection
OAMS	orbital attitude and maneuvering system

Term or Symbol	Definition
operating pressure	nominal ullage pressure to which the tanks are subjected under steady-state conditions in service operations
p	pressure
pH	negative logarithm of hydrogen ion concentration, a measure of acidity or alkalinity
proof pressure	maximum limit pressure (q.v.) multiplied by the proof-test safety factor. Proof pressure is the reference from which the pressure levels for acceptance testing are established.
Q	flaw shape and plasticity parameter, $Q = \phi^2 - 0.212\,(\sigma/\sigma_{ys})^2$
R	(1) ratio of minimum to maximum stress intensity during cyclic loading
	(2) ratio of the design load (or stress) to the allowable load (or stress)
r_y	plastic-zone radius of surface crack
RCS	reaction control system
SM	service module (Apollo spacecraft)
SPS	secondary propulsion system
STA	solution treated and aged
T3,T4,T6,T8,T73, T76,T87	designations for heat-treating and tempering processes for aluminum alloys
TIG	tungsten-inert-gas (welding method)
TVC	thrust vector control
t	material thickness
ullage	amount that a container lacks of being full
ultimate load (or pressure)	load (or pressure) at which catastrophic failure (general collapse or rupture) of the tank structure occurs

Term or Symbol	Definition
ultimate stress	stress at which the material fractures or becomes structurally unstable
W	weight
w	width
XFH	extra full hard temper
yield load	load that must be applied to the tank structure to cause a permanent deformation of a specified amount
yield stress	stress at which the material exhibits a permanent deformation of 0.0020 inch per inch (0.2 percent)
β	angle designating the location of K along crack front
Δ	incremental change in a quantity
ν	Poisson's ratio
ρ	material density
σ	applied stress; in a cracked specimen, stress remote from the crack
σ_{eff}	effective normal stress
$\sigma_x, \sigma_y, \sigma_z$	normal stresses acting on three mutually perpendicular planes of zero shear stress
σ_{ys}	material yield strength
ϕ	complete elliptic integral of the second kind, $\phi = \int_0^{\pi/2} \sqrt{1 - \left(\frac{c^2 - a^2}{c^2}\right) \sin^2 \theta} \, d\theta$

Material[1] (designation in monograph)	Identification
Metals	
A286	heat-treatable, high-strength austenitic steel
AM-350 AM-355 PH13-8Mo PH14-8Mo PH15-7Mo 15-5PH 17-4PH 17-7PH	semi-austenitic or martensitic precipitation and transformation hardening stainless steels
21Cr-6Ni-9Mn 300 series	austenitic stainless steels
1100	wrought aluminum (99% Al min.)
2014 2024 2219	wrought aluminum alloys with copper as principal alloying element
3003	wrought aluminum alloy with manganese as principal alloying element
D6Ac 300M 4130 4140 4335V 4340	high-strength martensite-hardening low-alloy steels
5052 5083 5086 5456	wrought aluminum alloys with magnesium as the principal alloying element

[1] Additional information on metallic materials herein can be found in the 1972 SAE Handbook, SAE, Two Pennsylvania Plaza, New York, N.Y.; in MIL-HDBK-5B, Metallic Materials and Elements for Aerospace Vehicle Structures, Dept. of Defense, Washington, D.C., Sept. 1971; and in Metals Handbook (8^{th} ed.), Vol. 1: Properties and Selection of Metals, Am. Society for Metals (Metals Park, Ohio), 1961.

Material (designation in monograph)	**Identification**
6061	wrought aluminum alloy with magnesium and silicon as the principal alloying elements
7075 7079	wrought aluminum alloys with zinc as the principal alloying element
HS 188 HS 25(L605)	cobalt-base high-temperature superalloys
HY140 9Ni-4Co-0.20C 9Ni-4Co-0.25C	martensite-hardening special category steels
Inconel 718	trade name of International Nickel Co. for precipitation-hardening nickel-chromium-iron alloy
low-alloy steel	steel with low carbon content
maraging steel	martensite- and age-hardening nickel-iron alloy
Waspaloy	designation of Pratt & Whitney Division of United Aircraft Corp. for a precipitation-hardening nickel-base superalloy
Nonmetals	
butyl rubber	synthetic rubber produced by copolymerization of isobutene with a small proportion of isoprene or butadiene
Cerrobend	trade name of Cerro Sales Corp. for the eutectic alloy of bismuth, lead, tin, and cadmium; m.p. 158° F.
Dacron	trade name of E.I. duPont Co. for a polyester fiber made from polyethylene terephthalate
Kapton	trade name of E.I. duPont Co. for a polyimide film (1 to 5 mils thick)
Mylar	trade name of E.I. duPont Co. for a polyester film made from polyethylene terephthalate
Nomex	trade name of E.I. duPont Co. for a high-temperature aromatic polyamide

Material (designation in monograph)	Identification
polyurethane	any of various thermoplastic polymers that contain -NHCOO- linkages; produced as fibers, coatings, flexible and rigid foams, elastomers, and resins
Teflon (TFE)	trade name of E.I. duPont Co. for polytetrafluoroethylene
Teflon (FEP)	trade name of E.I. duPont Co. for a polymer of fluorinated ethylene-propylene
TFE/FEP laminate	bladder made from numerous spray coatings of Teflon (TFE) on a mandrel with heat cure between each coat followed by numerous spray coatings of Teflon (FEP), also with heat cure between spray coats. Process was developed by Dilectrix Corp., Farmingdale, N.Y.

Fluids

A-50	50/50 blend of hydrazine and UDMH per MIL-P-27402
CRES	corrosion-resistant steel
FLOX	mixture of liquid fluorine and liquid oxygen
Freon	trade name of E.I. duPont Co. for a family of fluorinated hydrocarbons
helium	pressurant helium (He) per MIL-P-27407
hydrazine	N_2H_4, propellant grade per MIL-P-26536
H_2O_2	hydrogen peroxide
IRFNA	inhibited red fuming nitric acid, propellant grade per MIL-P-7254
LH_2	liquid hydrogen (H_2), propellant grade per MIL-P-27201
LOX	liquid oxygen (O_2), propellant grade per MIL-P-25508
MMH	monomethylhydrazine, propellant grade per MIL-P-27404
MON 10	mixed oxides of nitrogen (90% N_2O_4/10% NO)
nitrogen	gaseous nitrogen per MIL-P-27401

Material (designation in monograph)	Identification
N_2H_4	see hydrazine
NO	nitric oxide
N_2O_4	nitrogen tetroxide (oxidizer), propellant grade per MIL-P-26539
RFNA	red fuming nitric acid
RP-1	kerosene-base high-energy hydrocarbon fuel, propellant grade per MIL-P-25576
UDMH	unsymmetrical dimethylhydrazine, propellant grade per MIL-P-25604

Abbreviations	Identification
ABMA	Army Ballistics Missile Agency
AFFDL	Air Force Flight Dynamics Laboratory
AFML	Air Force Materials Laboratory
AIAA	American Institute of Aeronautics & Astronautics
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CPIA	Chemical Propulsion Information Agency
DMIC	Defense Metals Information Center
IIT	Illinois Institute of Technology
LPC	Lockheed Propulsion Co.
MSFC	Marshall Space Flight Center
TACOM	(Army) Tank-Automotive Command

Abbreviations	Identification
WADD	Wright Air Development Division
WPAFB	Wright-Patterson Air Force Base

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